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SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION. ALEXANDRIA. VIRGINIA

NOTICE:

CHAFF COUNTERMEASURES

AND AIR DEFENSE RADAR DESIGN

By: John H. Bryan

Prepared for:

REDSTONE ARSENAL OF THE U.S. ARMY ORDNANCE CORPS
HUNTSVILLE, ALABAMA
EVANS SIGNAL LABORATORY OF THE U.S. ARMY SIGNAL ENGINEERING LABORATORIES
FORT MONMOUTH, NEW JERSEY

STANFORD RESEARCH INSTITUTE

Applied Research Center of the West

MENLO PARK, CALIFORNIA

SRI

Apr 59

TR 6

Technical Report 6

CHAFF COUNTERMEASURES
AND AIR DEFENSE RADAR DESIGN

By: John H. Bryan,

SRI Project No. EU-2351-310

Prepared for:

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FORT MONMOUTH, NEW JERSEY
Under Contract Nos. DA-04-200-ORD-442 and DA-04-200-506-ORD-710
with the San Francisco Ordnance District, entitled Economic Recommendations
Concerning the Development of Army Ordnance Surface-to-Air Missile Systems

Approved:

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Copy No. **6** *of* 50

SECRET 0554

FOREWORD

This report was first published in August 1958 as an internal memorandum. In order to make this information more widely available, it is now being published as a technical report.

ABSTRACT

Chaff may be used in a variety of ways to protect attacking bombers from air defense radars. This report considers the operational problem of chaff as a threat to U.S. radars by first surveying the technical characteristics of chaff and of anti-chaff techniques and then examining a characteristic tactical chaff defense problem in the light of these technical characteristics.

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CHAFF COUNTERMEASURES AND AIR DEFENSE RADAR DESIGN

I INTRODUCTION

In the present era, the destructive potential of small numbers of enemy bombers has changed concepts of air defense from "attrition" to "total defense," and has made imperative the security of air defense radars against radar countermeasures. The basic problem of radar protection is complicated by the variety of countermeasures available to an enemy and the numerous possible modes of their employment. This report is devoted primarily to an examination of chaff used alone as a threat to the effectiveness of U.S. air defense radars.

Chaff can be used against both airborne and ground-based air defense radars in three basic ways: corridors, isolated random 'drops, and sudden bursts. The principal features of these methods of using chaff are outlined below:

> (1) Corridors. The primary objective of a chaff corridor
>   is to hide bombing aircraft from the search and
>   tracking radars used by a defense system. To hide
>   the aircraft it must create and sustain for some time,
>   over a continuous region, (single trail, multiple
>   trail, or area) a clutter level that masks the radar
>   returns from the aircraft. To prevent identification
>   of the aircraft at the head of a trail, the chaff may
>   be at least partially sown by forward-launched
>   missiles, which may or may not also serve as decoys.
>
>   The effective clutter level for a chaff corridor will
>   depend on several factors: the density of the chaff,
>   the chaff echoing area per unit weight at the trans-
>   mitted frequency, the dimensions of the corridor, and
>   the sub-chaff visibility of the radar.
>
> (2) Isolated Drops. Randomly or pseudo-randomly spaced
>   drops of chaff over an extensive area are designed to
>   introduce confusion by presenting many false targets
>   from among which a search radar operator must dis-
>   tinguish the real target aircraft. In addition to

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this effect, track-while-scan computers used with
automatic acquisition may be saturated with the
large reported number of apparent targets.

(3) Burst Chaff. The technique of suddenly ejecting
several bundles of chaff is used to prevent a
tracking radar from acquiring the aircraft in
its tracking cell and beginning a tracking en-
gagement, or to break the tracker's lock after
an engagement has begun. If this technique is
successful, the tracking radar begins tracking the
chaff cloud. Burst chaff is useful primarily
against automatic tracking systems such as air-
borne intercept radar, where the rate-aided-manual
mode of operation is not practical for avoiding
false targets. Its effectiveness depends on the
geometry of the situation, the relative speed and
range of the target, the dispersion rate of the
chaff, and the radar range servo response charac-
teristics. Forward-launched chaff rockets may be
used to extend the usefulness of the chaff bursts
against sophisticated trackers.

There are, at present, at least three compelling reasons for a
close look at the chaff vulnerabilities of U.S. air defense radars.

(1) Many of these radars now in operation were designed
with no consideration of the threat of chaff, and
have very little capability against it.

(2) Fundamental relationships limit the protection that
can be provided simultaneously in a radar design
against a combination of chaff and noise jamming.

(3) The Soviets are known to employ chaff in tactical
exercises and thus must be assumed to be fully
aware of its capabilities and ready to use it if it
will help to protect their aircraft.

The over-all effect of the strategic threat of chaff is to require
an investigation of the chaff vulnerability of present and projected
radars and perhaps to call into question the conventional techniques
that are depended upon for reducing chaff interference. Fundamental
approaches to ECCM capability need to be examined in connection with
anticipated attack situations to appraise their mutual compatibility
and combined effectiveness in meeting the threat of ECM.

The remainder of this report considers the problem of chaff as a
threat to U.S. radars, first by examining the basic properties of chaff

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as a collection of random scatterers with varying return (Sec. II).
Some of the operational aspects of the chaff problem are then emphasized
in a discussion of the means that may be used to deliver chaff
effectively against U.S. radars (Sec. III). In Sec. IV the means for
protecting radars against saturation by chaff clutter are described
qualitatively, along with the moving-target-indication circuitry re-
quired to obtain subchaff target visibility in a dense clutter region.
In Sec. V the subchaff visibility of two representative U.S. air de-
fense radars is examined quantitatively in view of the types of chaff
delivery anticipated in Sec. III, and some preliminary conclusions are
drawn. Finally, in Sec. VI a number of questions raised by an investi-
gation of chaff are presented, with suggested information requirements
for further evaluation.

II BASIC CHAFF CHARACTERISTICS

A. COMPARISON OF CHAFF AND NOISE JAMMING

The fundamental operational and technical properties of chaff that make it a threat to effective radar operation may be illustrated by comparing it with noise jamming. The similarities and differences may help to point out the problems of providing a defense against this form of interference.

1. SIMILARITIES TO NOISE JAMMING

a. Operational

Chaff, like noise jamming, is used primarily for screening attacking aircraft by providing a clutter signal that is intended to mask the radar return from the aircraft. Like jamming, it (1) requires the use of auxiliary equipment with an attendant weight penalty; (2) can originate either at the aircraft itself or at an auxiliary vehicle such as a decoy; and (3) may be used by aircraft for mutual protection as well as for self-protection.

b. Technical

Chaff, as well as jamming, may be used to cover relatively narrow portions of the frequency spectrum or, less efficiently, to provide clutter over large frequency bands. (U.S. chaff developments have been directed toward providing wide-band coverage* for years; narrow-band packaging may, however, permit considerable saving in the weight penalty of chaff sowing.)

what is chaff?
what is rope?

---

* Wide-band chaff consists of a number of lengths of chaff dipoles with or without rope, packaged together.

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2. DIFFERENCES FROM NOISE JAMMING

a. Operational

Unlike jamming, chaff creates a purely local effect which depends on the location of the dispensed chaff. It does not create a noise strobe, for example, on a PPI display, but instead presents an apparent discrete target or a continuous reflecting trail or area of limited dimensions. It cannot be switched on instantaneously; there is a time delay in the dispersion of the chaff dipoles before the mass appears as a target; and (except for special types) it persists after dispensing for a relatively long time (perhaps an hour) if dropped from medium altitudes.

Chaff is unlike jamming, too, in that the supply of chaff materials is continuously diminished as the chaff is dispensed; this supply can be exhausted in a relatively short time or can be spread out over a longer period, depending on the quantities available and the dispensing rates.

Another difference, which may be operationally useful, is that whereas noise jamming reveals the angular coordinates of the jamming source, a chaff corridor may not reveal the angular coordinates of the aircraft within it. Whereas jamming may be used to break lock of a conically-scanned tracker, chaff may be required against a mono-pulse tracker. There is a similarity, however, between jamming that creates a one-dimensional ambiguity in range and a thin chaff trail which also creates a one-dimensional ambiguity in target position along the trail.

b. Technical

Chaff return differs basically from a wide-band, noise-jamming signal in its pulse-to-pulse coherence. Whereas wide-band noise samples at a given range interval on successive range sweeps will be independent, chaff returns or clutter, in general, will not, since only a limited motion of the clutter-producing dipoles can take place in the very short time between pulses. This relative coherence or correlation between successive chaff returns suggests a possible basis for reducing them:

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cancellation of the common amplitude level of successive returns by a combination of delay and subtraction (effectively a range-gated differentiating circuit). Depending on the correlation of target returns, some advantage in target visibility might be gained by this means; nothing would be gained, of course, if the interfering signal were wide-band noise instead of chaff.

Another basic characteristic of chaff returns is that the clutter power level is proportional to the transmitted power level. Hence, an increase in radiated power, a measure that is helpful against noise jamming, yields no improvement against chaff.

B. TECHNICAL CHARACTERISTICS OF CHAFF

A more detailed description of the technical characteristics of chaff will be useful in providing an introduction to the technical problems in radar protection against chaff clutter. The variations in chaff returns and their statistical description are important in understanding the different functions of basic anti-clutter circuitry and particularly in evaluating the effectiveness of velocity discrimination techniques. The relationship between chaff correlation time and radar scan time leads to conclusions about chaff density requirements. Rates of chaff dispersion and fall are important in some operational questions. Finally, a numerical illustration of frequency coverage will show how the chaff space and weight allowances in a bomber may be used to cover either a wide or a narrow band of frequencies, and how the chaff may be packaged for convenient use.

1. CHAFF RETURN VARIATIONS AND THEIR STATISTICAL DESCRIPTION

When a package of chaff opens to release its contents, whether by explosion of a self-contained charge or by the action of a mechanical dispensing system, the chaff dipoles immediately begin to disperse and the rope spools (if any) unwind. Measurements indicate that several seconds, on the average, are required for a package of chaff released from an aircraft to "bloom", through dispersion of the dipoles, to its full or rated echoing area. The amplitude of the radar return from a chaff cloud is not at all constant, however, even after the chaff has

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bloomed, but fluctuates as a function of time between wide limits. The
variations in amplitude and rates of fluctuation can be described with
some success by statistical parameters. A qualitative basis for this
statistical description is outlined below.

Several types of variations are of interest in anti-clutter design.
These have similar statistical descriptions but affect target visibility
in different ways and must be distinguished.

a. Variation with Aspect

This variation depends on the relative positions of the di-
poles with respect to the viewer. To illustrate this effect, let us
consider that the chaff is illuminated and viewed by a radar that is not
scanning in azimuth. Let us also assume that the chaff cloud is no
larger than one radar resolution element and that the dipoles are not
moving. The return from this chaff cloud will depend upon the direction
of illumination, since the phase relationships between the returns from
individual dipoles vary with this direction. Equivalently, for a given
direction, the return will depend on the spatial distribution of the
dipoles. If the dipoles are distributed randomly in the small cloud,
the amplitude of the return may lie anywhere between a value close to
zero, corresponding to phase cancellation of the returns of the indi-
vidual dipoles by each other, and a large value corresponding to phase
reinforcement of these returns. If a large number of independent[*],[1],[**]
observations are made of the cloud of dipoles, the amplitudes of the
returns will be found to follow, to a close approximation, the Rayleigh[***]

---

* Independence of observations in this hypothetical situation could
  be achieved by a large number of identical radars at the same range
  but spaced angularly about the cloud. If the cloud is not too
  close, observations can be made independent if these radars are lo-
  cated tangentially a distance approximately $d = n\lambda/2\phi$ apart, where
  λ is the wavelength, ϕ is the beamwidth, and n $\neq$ 1, 2, 3, ...
  (Ref. 1, p. 983).

** References are listed at the end of the report.

*** This is equivalent to a Gaussian distribution of the in-phase and
  out-of-phase components of the return, as determined by coherent
  phase reference at the receiver.

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probability distribution, in which the probability of an amplitude A is

$$p(A)dA = \frac{2A}{\overline{A^2}} \exp\left(\frac{-A^2}{\overline{A^2}}\right) \, dA$$

where $\overline{A^2}$ is the variance of the amplitude A.

b. Range-to-Range Variation

If the cloud of stationary dipoles that we have considered is extended in range so that it occupies several resolution cells, the return to our non-scanning radar will be extended in time, and its envelope may fluctuate even if the cloud is uniformly dense (each resolution cell containing the same number of dipoles). Samples of the chaff return measured at times separated by τ, the pulse duration, will be independent, since the contributing dipoles will all be different (each dipole being illuminated for just τ seconds). The signals reflected from dipoles contributing to successive samples will have different phase relationships; these samples will, accordingly, have amplitudes governed closely by the Rayleigh probability distribution, and the envelope of the return will fluctuate between these amplitudes.* This variation is, of course, independent of the R^{-4} variation in amplitude of return with increasing range R of the chaff from the radar. Significantly, however, not only the mean level but also the amplitude of range-to-range fluctuations of chaff returns varies as R^{-4}. In this respect the chaff returns are like ground clutter. ✓

c. Variation Introduced by Azimuth Scanning

Returning to the small cloud of dipoles, let us keep these dipoles stationary but allow the radar to scan in azimuth. Successive pulses illuminating the cloud will have different amplitudes,

---

* Since the pulse of energy, as it moves along in range, is almost continuously illuminating new dipoles and ceasing to illuminate others, there will be high-frequency fluctuations in the return corresponding to the propagation velocity of the pulse and the spacing between dipoles in range. The pulse rise time and radar pass band will smooth out these high-frequency fluctuations, however. It may be noted that regardless of the radar bandwidth, successive samples of return will not be independent unless they are separated in time by at least τ.

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corresponding to the shape of the transmitting antenna beam, and the return will be similarly modulated by the shape of the receiving antenna beam. In addition, as the cloud is scanned in azimuth, new dipoles are illuminated and "old" ones pass out of the beam on successive pulses; the signal response from the cloud fluctuates correspondingly in both amplitude and phase. Thus scanning of the radar introduces pulse-to-pulse variations in the return from the chaff cloud.

d. Variations with Transmitted Frequency

Next, let us stop the radar's azimuth scan, keeping the dipoles fixed in position, but change the transmitted frequency slightly. The phases of the individual dipole returns both with respect to the radar and with respect to each other will now be changed slightly. It is the latter that determines the amplitude of the resultant return. If there are n cycles of RF energy in each pulse to begin with, this number can be increased to $n + 1$ by increasing the frequency by an amount equal to the reciprocal of the pulse length. This is sufficient, if the dipoles are well distributed throughout a resolution cell, to produce a change in the phases of the dipoles with respect to each other sufficient to make the amplitude of the resulting return substantially independent of that obtained at the original frequency. Since the pulse length is generally the reciprocal of the IF bandwidth, a change in transmitted frequency by this bandwidth on two successive looks at a given resolution cell filled with chaff will generally result in a pair of independent returns (Ref. 1, p. 981).

e. Fluctuations Produced by Random Motion

Next, let us keep the radar stationary in azimuth and keep the frequency fixed, but permit the dipoles to disperse in their normal fashion, falling and being blown about by local winds. The distances that the dipoles move between pulses will determine the differences in phase of the contributions of the dipoles and the corresponding differences in amplitude and phase of the returned pulses. For low wind velocities, the resulting differences may be quite small but will depend

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on the repetition period and the transmitted wavelength of the radar.*
If the wind is uniform in speed and has a fixed radial velocity with
respect to the radar through the chaff-sown region, there will be a
periodic component of phase shift between pulses. Turbulence in the
air will produce a variation in dipole velocities resulting in a re-
distribution of their respective phase contributions and variations in
the net inter-pulse phase shift about the periodic component. The
amplitude of the return will also fluctuate from pulse to pulse as the
contributions of the dipoles add in somewhat different phase relation-
ships. Unless a great deal of reshuffling of the dipoles takes place
between pulses, however, the returns from these pulses, interpreted as
samples of a continuous change of amplitude and phase, will not be
statistically independent; in other words, there is a dependence or
correlation between successive returns from the same bunch of chaff.**
The normalized time-average autocorrelation function evaluated at the
pulse repetition interval will, in general, be neither zero nor one but
somewhere between. Measurements have indicated that the internal motion
of a chaff cloud produces a signal with a smoothly decreasing auto-
correlation function, approximately Gaussian in shape, its width in-
versely proportional to the rms wind velocity. The corresponding power
spectral distribution of the fluctuating chaff return is also approxi-
mated by the Gaussian form and is given[2] by

$$W_{im}(f) = \frac{\lambda}{2V\sqrt{2\pi}} \exp\left(\frac{-\lambda^2 f^2}{8V^2}\right)$$

where λ is the RF wavelength, $\underline{f}$ is the clutter frequency, and $\underline{V}$ is the
standard deviation of the random dipole velocities about the mean

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* Perhaps it should be emphasized that we are not considering a gross
   displacement effect. The speed of chaff dipoles in the wind is not
   great enough to move them from one range cell to the next between
   pulses. (E.g., in a 100-knot wind, the chaff would move 5 cm between
   pulses if the radar had a repetition rate of 1,000 pulses per second.)

** If the dipoles were completely randomly redistributed between pulses,
    the returns from a series of pulses would have randomly varying ampli-
    tudes following the Rayleigh distribution.

velocity of the chaff cloud. (The subscrip: im stands for internal motion.) The unit-power spectrum of amplitude fluctuations has the form shown in Fig. 1 if the mean velocity is zero.
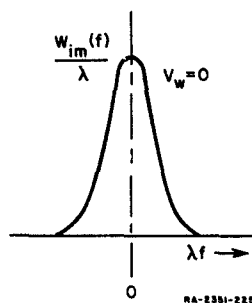
FIG. 1

UNIT-POWER CHAFF SPECTRUM
FOR ZERO MEAN VELOCITY
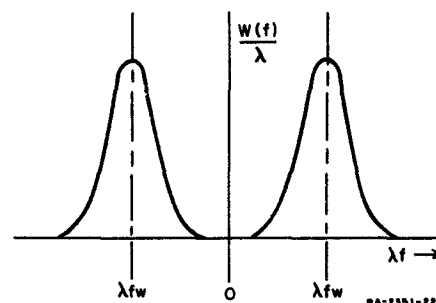
FIG. 2

UNIT-POWER CHAFF SPECTRUM
FOR NON-ZERO MEAN VELOCITY

If the chaff cloud has a steady drift component of radial velocity with respect to the radar, the returned echoes will have a doppler shift in frequency. This may be measured in a pulsed radar by means of a signal in the receiver whose phase is coherent with that of each transmitted pulse. Using this signal for coherent detection of returns from chaff having a steady radial drift component V_w, the spectrum of the resulting video amplitude fluctuations is shifted along the axis away from zero by a frequency $f_w = 2V_w/\lambda$ as shown in Fig. 2. This figure may probably be best thought of as depicting the superposition of fluctuation frequencies on the drift doppler frequency. The power spectral distribution then becomes:

$$W(f) = \frac{\lambda}{2V\sqrt{2\pi}} \exp\left[\frac{-\lambda^2(f-f_w)^2}{8V^2}\right] .$$

2. CORRELATION TIME, INTEGRATION TIME, AND CHAFF DENSITY REQUIREMENTS

In order to provide a clutter signal that actually masks the aircraft return, the chaff must occupy the same resolution cell as the aircraft. To provide a continuous clutter source, with no visible

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breaks in the trail or corridor, chaff must occupy each resolution element in the space through which the aircraft is to be screened. This fact has led to a conventional rule-of-thumb which states the chaff density requirement as one equivalent cross section per resolution cell. We shall next consider briefly how this requirement may be modified, assuming for simplicity throughout the discussion that the radar does not have advanced moving-target discrimination capability against chaff.

The chaff quantity requirement, as might be expected, depends on the type of radar--i.e , whether search or track--and on the way in which it integrates the pulse returns during its acquisition phase. It depends, too, on the number of independent clutter samples provided by the chaff during the scan or acquisition time.* This number will be inversely proportional to the correlation time of the chaff, defined as the time for which the (Gaussian-shaped) autocorrelation function of the chaff has dropped effectively to zero. For a search radar, the look time or scan time is the interval during which the antenna beam scans the target. For a tracker, it may be the time during which an aircraft flies through one resolution cell of the radar (e.g., through the range gate or through the beam).

Hult has shown (Ref. 3, p.3) that if the look time or scan time of a radar is greater than the correlation time of the chaff, the total quantities of chaff required are not a sensitive function of the radar resolution, but depend on the chaff decorrelation, which is a function of the radar frequency. The net result is that for such radars (primarily, it appears, high-frequency tracking radars), no great increase in chaff density is required if the pulse length is simply shortened.

For radars whose scan time is short compared with the chaff correlation time, the chaff density requirement is determined by the

---

* The more chaff return samples integrated, the more "decorrelated," noiselike, or "non-targetlike" the chaff return.

requirement to have a masking clutter-signal source in each resolution element. This does not mean that the chaff return from each element must at all times equal or exceed the aircraft return--such a requirement could not be met by chaff, since its return may drop occasionally to an amplitude close to zero.* It appears that to create sufficient confusion to radar operators to interfere seriously with detection, it is necessary only to have a moderate clutter level with "highlights" appearing and disappearing continuously in the trail or corridor (due to local reinforcing interference) which equal or exceed the aircraft return. To produce such a clutter signal along a trail or corridor, a relatively small amount of chaff is required. In a freshly sown trail, for example, if the aircraft cross section is σ, it can be effectively screened by chaff sown in quantities of cross section $\sigma/5$ per resolution cell. Even less is required if the chaff has dispersed for some time, decreasing the correlation time and increasing the frequencies of scintillation.[3]

The amount of chaff required will, of course, increase if the radar is equipped with a system for moving-target discrimination that gives the radar some subchaff visibility. This will be discussed in Sec. V.

3. DISPERSION AND FALL RATES

A limited amount of information, apparently conflicting, is available on dispersion rates of chaff. In particular, there appears to be no information on differences in dispersion rates when chaff is dispensed from various vehicles at high altitudes, or differences between rates for, say, foil and fiber chaff dipoles. Some information of general interest is available, however, from which some conclusions about dispersion effects may be inferred.

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* Whether this condition is actually observable on a radar display will depend, of course, on whether the display exploits the full resolution capability of the remainder of the radar, whether it limits at a relatively small echo amplitude, and whether the chaff clutter level and variations can be distinguished from receiver noise.

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Foil dipoles released from dispensers in the fuselage or wingpods
of an aircraft scatter on contact with the slipstream, dispersing in all
directions. According to some observations, immediately after dispensing
from high-altitude aircraft, the heavy chaff from a broad-band package
falls at rates up to 600 feet per minute while the lighter chaff tends to
rise slowly for a period of approximately five minutes and then remains
stationary for another ten minutes before starting a steady rate of de-
scent. After a few minutes the rate of fall of both the top and the
bottom of the cloud begins to stabilize. The greatest response from the
chaff is slightly above the center point between the top and bottom. This
bright portion or core is reported to be greater than 4000 feet in depth
and to fall at a steady rate for approximately 90 minutes, after which
the chaff response begins to fade and become isolated. This core has a
rate of fall of approximately 300 feet per minute in the 30,000- to
40,000-foot interval of altitude.[4] Chaff will disperse horizontally in
two ways: If there is a wind, it will have a general motion imparted by
the air mass, and it will also have a dispersion rate about the mean wind
velocity which will depend on the gustiness of the wind and on wind shear
at the altitudes through which it falls. Measurements indicate that the
dispersion velocity of chaff has a standard deviation on the order of two
knots. This figure agrees with a report of Air Proving Ground Command
that if dispensing aircraft are separated laterally by two or three
miles, the individual streams will merge between 10 and 30 minutes after
the chaff is dispensed, the period depending on the wind gradients and on
the displacement of the corridor from the ground radar. For closer air-
craft spacings, the time required for merging would be expected to be
reduced approximately in proportion.

4. FREQUENCY COVERAGE

The bandwidth of a single foil dipole is about 15 percent of center
frequency. Only seven lengths of dipole are required to cover the fre-
quency band from 2,500 to 1,000 Mc with a return within a few decibels,
as shown in Fig. 3, which gives an approximate breakdown of the U.S.
standard foil chaff package RR-39/AL. The total weights of dipoles are
about the same at each of the seven frequencies. The 15-percent

RADAR CROSS-SECTION — sq ft

INDIVIDUAL DIPOLE LENGTHS
COMPOSITE
COMPOSITE CALCULATED BY
STANDARD ROLLING MILLS*

FREQUENCY—Mc
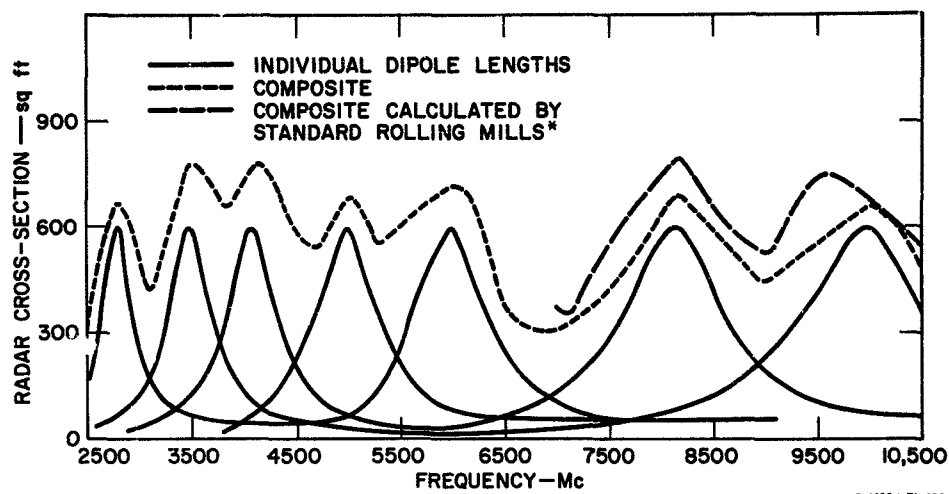
* Final Engineering Report on Research and Development of Advanced Radar Confusion Techniques,
Standard Rolling Mills, Dec. 31, 1955, p. 186, SECRET.

FIG. 3

APPROXIMATE COMPOSITION OF RR-39/AL BROAD-BAND FOIL CHAFF PACKAGE
theoretical cross-section vs frequency of individual dipole lengths
and composite package neglecting harmonic responses

bandwidth of a single length of dipole is large enough to cover the
tunable band of any radar used at present or planned for the near future
in this country. Thus, against specific radars, the packaging of chaff
can be made considerably more efficient than in the broad-band package
if a single length of dipole is used per package. The practicability of
such narrow-band packages will depend on how much is known about the
frequencies of enemy radars, the information being supplied by intelli-
gence sources, electronic reconnaissance, or both.

Since the U.S. standard packages were developed, efforts have been made
to further reduce the bulk and weight of chaff by using narrower widths and
by using aluminized glass filament dipoles in place of the foil dipoles.
As the chaff is made narrower, the bandwidth of the individual dipoles
decreases somewhat, but this decrease can be compensated for by using a
slightly larger number of dipoles, cut, perhaps, to slightly different
lengths. Notable among U.S. chaff developments is the RR-66 package of
fiber chaff, which weighs about three ounces and covers with the same
cross section the same band as the one-pound RR-39/AL package.

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III ANTICIPATED DELIVERY SYSTEMS

The way in which chaff is sown may have a strong influence on its success in protecting bombers against air defense radars. Each method of sowing requires a delivery system with certain capabilities and some limitations. These systems must be examined in order to estimate the quality and quantity of protection that a bomber may obtain by means of chaff. They also suggest the attack situations in which chaff may be most helpful and those in which its use is questionable.

A. CONVENTIONAL MECHANICAL DISPENSERS

U.S. aircraft are currently equipped with mechanical chaff dispensers whose dispensing rates are governed by an adjustable control mechanism (intervalometer). The dispensers are carried either in the fuselage or in wing pods. Chaff from these dispensers blooms behind the aircraft and forms either a continuous trail or a pseudo-random pattern of false targets. The control may also be used to eject large bursts of chaff periodically (every few seconds) to interfere with tracking radars. An alternative system ejects chaff bursts on a signal from a warning receiver that indicates that the aircraft is being illuminated by a tracking radar.

Mechanical dispensers of this type are very useful for large-scale operations where a large number of aircraft participate and where it is desired to sow large areas or long corridors with chaff. In such a situation some aircraft may be assigned the function of ECM aircraft, carrying countermeasures equipment alone as payload, while other aircraft carry bombs as well. Dispensers of this type are also useful for concealing the number of aircraft engaged on a bombing mission and contained within a corridor or area. They appear to be useful, too, against airborne intercept radars in tactical engagements, to the extent that these radars can be forced to break lock by burst-chaff methods.

Mechanical dispensers appear to be least useful when a small number of aircraft attack a target; that is, when chaff must be depended upon for self-protection. The basic reason for this is simply that since the chaff blooms some distance behind the aircraft, a high-resolution radar can resolve the lead chaff-dispensing aircraft from the chaff trail and direct weapons against that aircraft. As other aircraft, following the lead aircraft in the chaff trail, emerge from it, they too can be resolved, even if they are dispensing chaff. In this situation, the lead aircraft, at least, needs additional protection; jamming, for example, might be used to obscure its position. If jamming is to be avoided (as, for example, in anticipation of home-on-jamming seeker missiles) other alternatives such as decoys and forward-launched chaff or combinations of these, may be used.

B. FORWARD-LAUNCHED CHAFF

It appears that current U.S. planning for bomber protection by forward-launched chaff calls for two principal types of chaff-sowing vehicles: a short-range rocket or "deflection missile"* for range-gate stealing and breaking lock of leading-edge tracking radars, and a longer-range "screening" missile for chaff-sowing against search radars. These could be used to create a single trail, or possibly multiple trails, ahead of the aircraft. With some cooperation between bombers assigned to the same target, a somewhat wider trail or a larger number of trails might be established. These appear to be fundamental methods of forward-launching chaff from which an enemy could choose for the protection of bombing aircraft against U.S. defense radars.

To estimate the possible effectiveness of these techniques, the following parameters are important: the distance between the bomber and the forward edge of the chaff trail; the density of the trail; and the length of time (or distance) over which the trail can be maintained.

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* The word "deflection" here describes the path of the missile, which is deflected out of the path of the dispensing aircraft by gravity while flying ahead of the aircraft.

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These are all functions of the type of dispensing vehicle carried by the bomber.

In choosing appropriate chaff-sowing vehicles, an enemy will be guided by the following considerations: his estimate of the lethal radius of surface-to-air and air-to-air missile warheads; his estimate of the chaff densities in pounds per mile required to screen the aircraft against the defense system radars; and the required total dispensing time.*

C. CHAFF DENSITIES REQUIRED

The required chaff densities will depend, in turn, on the radar cross section of the bomber in the direction of the radars, the frequency band to be covered, the efficiency of the chaff in radar cross section per pound of chaff materials, and the subchaff visibility of the radars. The last of these factors is discussed in greater detail in Sec. V of this report.

Some idea of order of magnitude may be obtained by assuming no subchaff visibility. The radar cross section or echoing area of a large bomber (B-52 size) over the frontal aspects is in the range 20 to 40 square meters at most frequencies above VHF (Ref. 3, p.8). Using the figure (from Sec. II) for a rapid-scan search radar of $\sigma/5$ per resolution element, enough chaff must be provided to produce about 4 to 8 square meters of echoing area per radar pulse length of penetration distance. For a search radar with a 1-µs pulse, this would be 4 to 8 square meters for each 500 feet travelled. The weight of this required quantity of chaff is an important operational consideration.

One length of U.S. standard foil dipoles, 0.036 inch wide by 0.0004.5 inch thick, cut at S-band to yield 60 square meters of echoing area, weighs about two ounces. To obtain 60 square meters of echoing

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* Possibly the number of anticipated interceptor engagements as well, depending on the time period under consideration and the relative threat of interceptors vs. missiles to the bomber.

see table to give chaff weight, etc

area at X-band, about four ounces of dipoles are required.* Hence, for
each n.mi., against an S-band search radar of known frequency with a
1-μs pulse, the weight required would be about (6080/500) x 8 sq.m. x
[(2 lb./16)/60 sq.m.] $\approx$ (2 lb./n.mi.) for 8 square meters of echoing area
or one pound per n.mi. for 4 square meters using standard foil chaff.
If narrow foil chaff were used (0.008 inch wide), this weight requirement
could be cut by a factor of 4, with some sacrifice in bandwidth. By the
use of fiber chaff it might be cut by another factor of 2.

For a conventional tracking radar at X-band (e.g., the Nike Tracker
with 1/4-μs pulse width), the quantity of chaff required, considering
integration and correlation effects, has been estimated at about 70 σ
per n.mi. (Ref. 3, p.7). For a bomber of B-52 echoing area, about
40 square meters, this is 2800 square meters per n.mi. This quantity of
standard foil chaff would weigh about 2800/60 x 4/16 or 12 pounds per
n.mi. This again could be reduced by use of narrow foil or fiber chaff.

If estimates of the required chaff densities are increased in view
of anti-chaff techniques used by the radars to achieve subchaff visi-
bility, the fuel carried by a chaff-sowing missile may be appropriately
decreased so that the missile's increased chaff load will be properly
distributed over its shorter flight path.

D. DISPENSING TIME

The minimum time of flight for a chaff-sowing missile will be de-
termined, of course, by the requirement for the vehicle to dispense the
chaff a minimum distance ahead of the aircraft as determined by the SAM
or AAM warhead lethal radius. The maximum time of flight might be de-
termined by the distance over which the protection of a chaff trail is
desired; for example, between line-of-sight (detection) range--or some-
what beyond-- and the range at which a bomb or ASM has been launched
against the ground defenses--or has destroyed them. The detection range

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* Based on breakdown of RR-39 package. In general, the weight required
  to achieve a given cross section at center frequency with chaff di-
  poles of constant width and thickness tends to vary as f, the center
  frequency.

will be, of course, a function of altitude, as will the bomb release
line.

As examples, consider a high-altitude attack (on the order of
40,000 to 60,000 feet) and a low-altitude attack (200 to 1,000 feet).
The first might correspond strategically to a mass raid against CONUS;
the second might correspond to a sneak raid against SAC bases. Bombers
at 50,000 feet would probably be detected at about 250-n.-mi. range.
Assuming that they would drop chaff continuously over such a range, the
lead aircraft might well use forward-launched subsonic "screening
missile" chaff sowers of range capabilities of about 100 n.mi., if
three or four such missiles could carry enough chaff to degrade radar
performance considerably. This, of course, would depend on the radars
against which the chaff is to be used.

In a low-altitude attack, the use of screening missiles is probably
unnecessary as well as infeasible. The use of short-range chaff rockets
to disturb tracking and increase miss distances of low-altitude missiles
(with HE warheads) should possibly be considered, but ECM requirements
appear to be minimized in such an attack. It is not known that any
planning of low-altitude ECM tactics has been done for U.S. aircraft. A
considerable amount of planning has been done for high-altitude attacks,
however, and some of the results may be utilized here.

Hult[5] has estimated that a short-range deflection rocket or missile
might be made to provide 1-1/2 n.mi. of chaff trail in 10 seconds with a
terminal separation of at least 3,000 feet from the aircraft for a total
system weight (including launching facilities) of 30 pounds per missile.
The trail thus sown would have a density of 10 pounds per n.mi.; the
chaff payload would be about 50 percent. Similarly, a missile providing
3 n.mi. of chaff trail sown in 20 seconds and a terminal separation of
at least 2 n.mi. from the aircraft could be obtained for a total system
weight of about 60 pounds per missile. Another might give 6 n.mi. of
trail in 40 seconds with 8-n.-mi. terminal separation for a weight
penalty of 120 pounds per missile.

The screening missile could be either supersonic or high subsonic. A supersonic missile could be activated by a warning receiver and attain a separation from the bomber in a few seconds, but would have a shorter range or lower fractional chaff payload than a subsonic missile. As an example of the latter, Hult suggests that the Quail might be adapted fdr this use with 300+ pounds of chaff payload and 100+ n.-mi. range for a total system weight of about 1,500 pounds per missile. These longer-range screening missiles introduce guidance and aircraft navigation problems which may prove to be severe. The subsonic missile, which would have to be programmed against ground defense radars, would probably be of much less use against interceptor attack than short-range deflection chaff-sowing rockets.

E. **BOMBER CHAFF LOAD**

The fraction of the payload of a bomber devoted to chaff systems is determined by a number of considerations, including estimated effectiveness, method of employment (trail, corridor, burst, or random drop), available volume and weight allowance, and type of defenses anticipated.

Some idea of the chaff load that a bomber may carry on a conservative bombing mission in the future may be gathered from the following comparative figures: It was reported by Lincoln Laboratory, (December 1955), (Ref. 6, p.63) that each B-47 bomber would normally carry 800 pounds of chaff in addition to 500 to 1,000 pounds of electronic jamming equipment. As much as 6,000 pounds of chaff could be carried with a corresponding sacrifice in bomb load. The U.S. B/RB-66 series of aircraft can carry up to 3,160 pounds of chaff by sacrificing bomb load, but can carry 1,160 pounds of chaff and four dispensers without such a sacrifice by means of a tail cone and two wing pods. Members of the Applied Physics Laboratory in an informal discussion, have indicated that a possible threat could include, as payload for a Bison or Bear on a round-trip intercontinental mission without refueling, 1,000 pounds of chaff with 4,000 pounds of jamming equipment plus a 2,000-pound bomb load. Goble, chaff consultant, estimates a Soviet threat including

500-1,000 "units" of chaff,[7] with weight of units unspecified but assumed to be about one pound each. The B-52 Bomber Defense System (ALQ-27) will be capable of dispensing 500 pounds of chaff.

As indicated in a preceding section, the U.S. Air Force is planning a bomber capability for forward-launching of chaff. The North American Weapon System 110A is reported to have provisions for 36 forward-fired chaff rockets, each dispensing at least 5 individual chaff units ahead of and below the flight path of the aircraft. The estimated rocket weight is 11.1 pounds. The ALQ-27 will have provision for about 40 such chaff rockets, in addition to the 500 pounds of conventionally dispensed chaff referred to above.

A small number of drone-sized vehicles can be carried. A B-52, for example, which can carry 8 Quails at 1,000 pounds each by sacrificing its bomb load, could probably carry 4 Quails adapted for use as screening missiles, as described by Hult, while retaining half of its bomb load. A Mach-2 bomber might carry 2 to 4 chaff-dispensing decoys capable of matching its speed, by sacrificing part or all of its bomb load.

F. MISCELLANEOUS COMMENTS

In the next few years the increasing capability of U.S. SAC forces to respond quickly to an early-warning alert and to effect speedy retaliation may well diminish the likelihood of a large-scale massed-formation attack by Soviet bombers. In this event, an attack might take the form of small numbers of bombers in isolated groups attacking simultaneously (approximately) various targets (e.g., SAC bases) about the country, from high or low altitudes. It might be expected, therefore, that a trend might develop toward enemy bomber self-defense against rapid-reaction-time defense systems, i.e., against SAM systems. (It seems unlikely if a group of attacking aircraft were small, that any could be assigned the role of ECM aircraft.) Such a trend would probably lead toward more reliance on forward-launched chaff than on chaff dispensed from the bomber itself.

It should perhaps be emphasized that the weight allowances for ECM estimated in Sec. III-C assume a round-trip bombing mission. There is no particular basis for such a conservative assumption in anticipating a Soviet bomber attack on CONUS defenses. The payload increase and increased ECM capability allowable on a one-way mission might, in fact, make such a mission attractive to the Soviets in circumstances where a round-trip mission might not be. On a one-way mission the total payload, including bombs, could be at least doubled. It could be expected that the weight allowance for chaff as well as for jamming could then be increased by at least a factor of 2.

IV RADAR PROTECTION AGAINST CHAFF CLUTTER

A. ANTI-CHAFF TECHNIQUES

The problem of modifying radars to meet the chaff threat received considerable attention during World War II. For years afterward, however, the radars built for U.S. air defenses were not designed to meet the increasing threat posed by development of more efficient chaff materials and improved dispensing systems. Finally, as a result of a general recognition of the effectiveness of electronic countermeasures, requirements for improved radar anti-chaff performance were formulated.

In response to these requirements a variety of basic anti-chaff techniques have been investigated experimentally, and some of these have been implemented in radar modifications and new designs. From the relatively crude moving-target indication circuitry of the M-33 and Nike Ajax acquisition radars, designers have turned to such schemes as coherent MTI with multiple cancellation or range-gated, lumped-constant filters to extend suppression of returns from ground clutter to low-velocity targets. It has been generally recognized, however, that improved anti-chaff performance can be obtained only at the cost of increased complexity, new developments, or compromise in some other performance characteristics.

In the following paragraphs specific measures for obtaining radar anti-chaff performance are discussed in principle. They can be conveniently grouped into five categories:

(1) Increased resolution

(2) Modified receiver response

(3) Decorrelation of chaff returns

(4) Velocity discrimination

(5) Video censoring.

These measures range from basic anti-clutter circuitry to techniques designed specifically against chaff. Although the over-all purpose of the techniques is the same--to reduce the clutter effects of chaff to an

effect similar to that of receiver noise--a basic distinction should be made between those whose primary aim is simply to avoid saturation by chaff returns and those that attempt to enhance target visibility.

1. INCREASED RESOLUTION

Increasing a radar's resolving power can reduce the clutter level by reducing the quantity of chaff illuminated by the radar in a given instant. The increase in resolution can be achieved in azimuth and elevation by using narrower beams and in range by using shorter pulses. Narrow beams, of course, require large antennas for low transmitter frequencies. Two radars currently under development, FPS-7 and FPS-27, have several beams stacked in elevation while maintaining narrow horizontal beamwidths. In other radars the peak power limitation encountered in shortening pulse widths while maintaining average power will be avoided by using CHIRP and other matched filter techniques[8] to shorten the return pulse in the receiver rather than in the transmitter. These techniques, although not primarily anti-chaff measures, have the general effect of increasing the densities of chaff required to produce a given clutter level in a non-limiting radar receiver.* As discussed in Sec. II, integration effects must be considered in evaluating the resulting increase in target detectability during acquisition.

Pulse-edge tracking, which is designed to reduce a tracking radar's vulnerability to burst chaff by discriminating against the leading or trailing portion of a target echo, may be considered to be a way of increasing a tracking radar's range resolution.

2. MODIFIED RECEIVER RESPONSE

For purposes of preventing saturation by large clutter returns, a number of circuitry techniques may be used, singly or in combination; these are the use of a lin-log amplifier or Instantaneous Automatic Gain

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* Since this report was written, the author has been informed of investigations by Roger Manasse of Lincoln Laboratories and by Westinghouse of methods of exploiting this clutter reduction effect for target enhancement by using very large bandwidths and matched pulses.

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Control (IAGC) for extending the effective dynamic range of the receiver, and such circuits as Fast Time Constant (FTC) for reducing the low-frequency components that characterize extended clutter.

As discussed in Sec. II, since chaff echo is composed of the contributions of a great number of relatively independent scatterers, the amplitude of response from an extended chaff cloud at successive range elements may fluctuate considerably, and is well described by a Rayleigh probability distribution. If any signal whose amplitude fluctuates in time in a manner determined by this distribution is applied to the input of a receiver having a logarithmic response, the resulting rms fluctuation about the mean at the receiver output is constant, independent of the rms amplitude of the input fluctuations* (Ref. 9, pp.646-647). The objective in using this type of receiver is to compress the rms fluctuations in the clutter return to the amplitude of receiver noise <u>at all ranges</u> and thus to present a uniform background for display of non-fluctuating targets.** A limit to its effectiveness is set by trace-to-trace correlation of the clutter returns and by the fluctuations of the target aircraft echo. It provides no subclutter visibility.

The mean level of the clutter returns may be removed with a differentiating fast-time-constant circuit. Used with either a non-limiting linear or a logarithmic receiver, this will reduce the intensity of range-extended clutter on the display and enable large targets to be seen within it. It is thus effective in helping to prevent reporting of false targets. It provides, however, no subclutter visibility.

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* The logarithmic receiver is also useful for preserving the beats produced by the return from chaff and the target. These beats, which would be lost in a limiting radar receiver, may be used to identify targets.

Still another use of the logarithmic response is to increase a receiver's dynamic range in order to prevent the spread of clutter frequencies, introduced by azimuth scanning, which would result from limiting. This may be an important effect, for example, in a radar such as FPS-28 using range-gated high-pass filtering to eliminate or reduce clutter effects.

** An alternative technique for producing this effect is IAGC with Detector Balanced Bias circuitry, as used against ground clutter.

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Another means of eliminating targets that are extended in range is video pulse width discrimination. One method of accomplishing this is to use a separate one-pulse-width delay channel, requiring coincidence between the leading edge of a signal in the delayed channel and the trailing edge of the undelayed signal, for target identification. This measure will eliminate to a great extent large blocks of clutter, but will provide no subclutter visibility.

3. DECORRELATION OF CHAFF RETURNS

A basic distinction between receiver noise and chaff returns is that ordinarily chaff returns are correlated from trace to trace for a period of time determined either by chaff motion or by radar scanning, whichever is shorter. If the chaff returns could be decorrelated from trace to trace, they would be more nearly noiselike and could be discriminated against by noise-suppression techniques. One means of decorrelating returns is by pulse-to-pulse frequency change by an amount greater than one radar IF bandwidth. (Ref. 1, p.980). Techniques for the detection of signals in clutter backgrounds by this means are being investigated at Lincoln Laboratories (Project CRAFT). Subclutter visibility is not expected, but the technique has been demonstrated to enhance visibility of strong target signals in a clutter background.

4. VELOCITY DISCRIMINATION

Techniques for velocity discrimination to reduce clutter depend on correlation of chaff returns from pulse to pulse to permit their elimination through cancellation or high-pass filtering. A variety of techniques are employed. These will be discussed individually below, under the general headings: "doppler" phase-shift MTI, true doppler detection, and absolute speed detection.

a. "Doppler" Phase-Shift MTI

A number of pulsed-radar MTI (moving-target indication) systems detect target radial velocity in terms of a phase difference between successive pulse returns. This phase difference occurs whenever the target moves a non-integral number of half-wavelengths in the radial direction in the interval between pulses. A phase reference must, of course, be

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established in order to detect the change in the phase from pulse to pulse. These phase differences are converted, in a mixer or a phase detector, to amplitude changes. The basic systems for pulsed radars, coherent and noncoherent, are discussed below.

(1) <u>Coherent MTI</u>. A coherent MTI radar generates its own phase-reference signal at the receiver, usually at the IF, by sampling the transmitted signal. Delay-and-cancellation circuitry or high-pass filtering is used to eliminate low-velocity target returns. This is illustrated in block diagram form in Fig. 4.

Figure 5 shows the response of a conventional two-pulse canceler, which subtracts the video target signals from two successive range sweeps. The abscissa unit, $\underline{n}$, is the
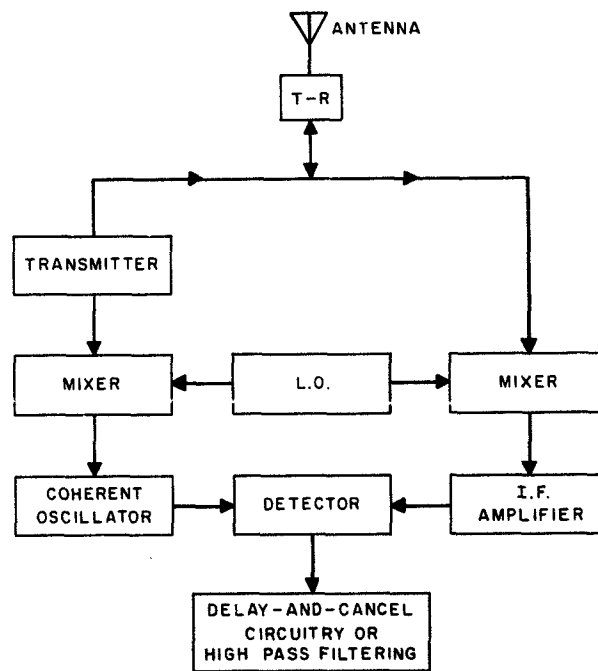
FIG. 4

BLOCK DIAGRAM OF CHARACTERISTIC
COHERENT MTI SYSTEM

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ratio of target doppler frequency to the radar repetition rate. This is also equal to the ratio of its radial velocity in knots to the quantity $[(291f_r)/f]$, where f_r is the repetition rate in pulses per second and f is the radar transmitter frequency in megacycles per second.

Originally designed to eliminate ground clutter, this technique can be extended to suppress returns from low-velocity chaff. The upper-velocity limit is set by the fact that to achieve good suppression at a relatively high chaff velocity while maintaining visibility of faster moving targets, the fraction of a half-wavelength (at RF) covered by the moving chaff in the interval between pulses must be made small, so that either very low frequencies (long wavelength) or very high repetition rates (short inter-pulse interval) must be used, or a combination of them. Very low frequencies, of course, make it very difficult to achieve angular resolution, whereas very high repetition rates limit the unambiguous radar range. (The so-called pulse-doppler radars are examples of the latter compromise.) Some suggestions have been made for means of extending the unambiguous range of search radars at high repetition rates, but it is not known that a successful method has been found.

Another reason for using a combination of low transmitter frequency and high repetition rate is to increase target visibility by decreasing the number of blind-speed bands within the range of velocities of expected targets. These bands are centered about the speeds corresponding to a target radial movement of an integral number of half-wavelengths between pulses ($n = 1, 2, 3, \ldots$ in Fig. 5). The width of the band is determined by the range of velocities suppressed, and is equal to twice this range at each of the blind speeds above zero. Thus, the greater the number of blind speeds, the smaller the range of speeds in which a target is visible and the larger the fraction of time that the target is not
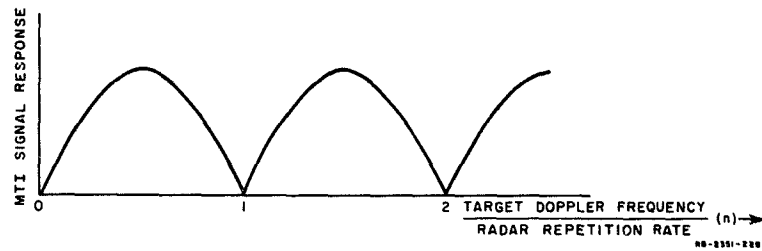
29

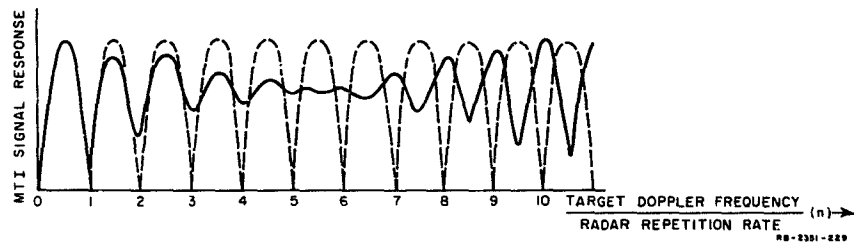FIG. 5 TWO-PULSE MTI CANCELER RESPONSE VS FREQUENCY

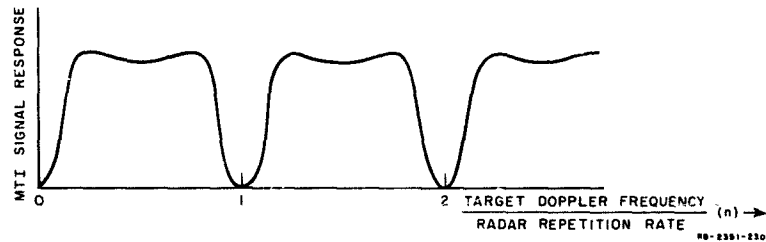FIG. 6 TWO-PULSE MTI RESPONSE WITH TWO REPETITION RATES

FIG. 7 EXAMPLE OF MTI RESPONSE OF THREE-PULSE CANCELLATION
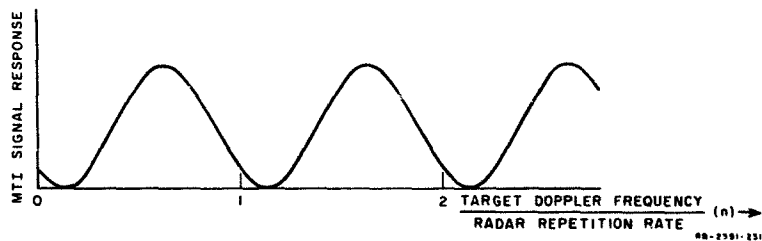WITH FEEDBACK CONTROL OF SHAPE

FIG. 8 EXAMPLE OF MTI RESPONSE OF THREE-PULSE CANCELLATION
WITH VELOCITY COMPENSATION

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visible (if the range of suppressed low velocities remains the same). If the pulse repetition period can be changed on alternate pulses or alternate scans, it is possible to stagger the blind-speed zones up to a given speed. The result is at least a partial filling-in of these zones, as shown in Fig. 6. The blind-speed effect can be minimized over any given range of velocities by proper selection of the ratio of repetition rates.

Delay-and-cancel circuitry is one form of filter for the amplitude variations of the pulse-train output of the radar detector. If the complexity of range-gated operation is permissible, however, somewhat more flexibility in the MTI characteristic response to low-velocity targets can be achieved by means of simple, lumped-constant filters. The coherent detector output signal (bipolar video) from the range gate for a single stationary target during a single scan is a series of pulses at the repetition rate, each pulse having a width limited either by the transmitted pulse length (for a point target) or the gate width (for a continuously-extended target). These gated output pulses have a frequency spectrum with components at multiples of the prf. A range cell which, instead, contains a moving target will have, in addition to these components, frequency pairs separated from the prf harmonics by the doppler frequency of motion. A boxcar circuit can be used to discriminate against the harmonics of the prf while maintaining the signal-to-noise ratio, and a high-pass circuit can be used to suppress low-velocity target returns.

The over-all filter characteristic can be made close to rectangular. For this system, by alternating repetition periods between successive pulses, a response curve with good blind-speed suppression can be obtained.

As an alternative to the simple high-pass filtering indicated for the range-gated radar, or in addition to it, the range-gated detector output may be distributed to a single narrow-band filter or to a filter bank. Pulsing the radar produces the periodic blind-speed pattern of response, so that the filters need

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only be distributed between zero and half the prf. Alternatively, a single narrow-band filter can be used with frequency tracking to keep the doppler frequency in the band, with a high-pass filter for suppression of low-velocity targets. A corresponding filter system for a CW radar must extend over the full range of anticipated doppler frequencies, chaff rejection being determined by the characteristic of the high-pass filter for a given chaff velocity spread. The possible objection to the large number of filters needed even for the wide-band, range-gated MTI (at least one filter per range interval) is somewhat mitigated by the elimination in a data processing system of range-quantizing equipment, and the possibility of Constant False-Alarm Rate (CFAR) operation.[6] A response curve approaching that for the range-gated filter MTI can be obtained by using multiple cancellation in delay line systems, with feedback loops around the cancellation circuitry. Such a response curve is shown in Fig. 7. In practice, the feedback may be adjusted to vary the response to low clutter frequencies. An example of this is in circuitry developed for the FPS-20 radar.

(2) Velocity-Compensated MTI. As discussed in an earlier section, the radial movements of chaff can be divided into two components: its uniform velocity (produced by the mean wind drift of the dipoles) and its internal motion or turbulence (produced by horizontal and vertical wind gradients). The uniform radial velocity component, which may be on the order of 100 knots at high altitudes, may prevent the suppression of the chaff returns in ordinary coherent MTI radar, but can be effectively removed by adjusting the reference phase of each pulse in a coherent receiver to compensate for it. (The same basic scheme is the standard method used to cancel the velocity component of a moving radar platform.)

If the direction of the wind is uniform across the chaff-sown area, its mean velocity can be compensated by varying the phase adjustment sinusoidally at a frequency equal to the scan angular frequency as the radar scans in azimuth. The velocity response of

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such a system, with $\underline{n}$ defined as in Fig. 1, is shown in Fig. 8 for a canceler using three-pulse cancellation. This method of combining pulses, which may be realized by placing two single-cancellation circuits in series, is generally referred to as double cancellation. The compensation indicated in Fig. 8 minimizes response to a target characterized by $n = 1/8$.

If the direction or amplitude of the wind is not constant over the chaff-sown area, a method of compensation called clutter-locked MTI can be used. The clutter-locked system locks a coherent oscillator in the receiver to the phase of the most recent clutter in successive intervals of a range sweep. This oscillator signal serves as a phase reference for moving targets until a block of clutter at a more distant range (and possibly a different radial velocity) changes its phase. The phase differences arising from differential radial motion between pulses of these blocks of chaff are automatically rejected by the phase-locking mechanism. Thus, at all ranges a reference signal is available (having a phase determined by local clutter), and the radar response to successive blocks of clutter at different radial velocities is minimized.

The basic limitation to velocity compensation as an anti-chaff device is that turbulent internal motion of the chaff may produce rapid fluctuations in the chaff return that exceed the band of fluctuation frequencies that can be suppressed, particularly if this band is narrow. From another point of view, the fluctuations in amplitude and phase resulting from reshuffling of the dipoles, which are more or less independent of the mean drift of phase, will produce clutter signals that simple phase adjustment of the coherent oscillator cannot compensate. The fact that these fluctuations in successive range cells are independent prevents the clutter-locked type of compensation.

For a given coherent MTI radar, however, velocity compensation can increase chaff return attenuation considerably if the air is not turbulent, and is certainly a worthwhile adjunct for a coherent-MTI radar. Although ground clutter will not be as

effectively suppressed if the mean velocity component is large,
it is doubtful that this will interfere with detection of targets
at near-maximum radar range. For a stacked-beam radar, in par-
ticular, the ground clutter problem in the velocity-compensated
MTI operation appears to be a minor one.

(3) Noncoherent MTI. Like velocity-compensated coherent
MTI, noncoherent MTI is a useful adjunct to ordinary coherent MTI
in a ground-based radar for detecting aircraft in uniformly-moving
chaff clouds. In contrast to coherent techniques, the noncoherent
MTI system uses the chaff (or ground) returns themselves as the
reference signal instead of using a signal generated at the re-
ceiver. Thus, it can be considerably simpler than, for example,
velocity compensation. It has the disadvantage, however, that a
clutter signal is necessary to detect non-fluctuating targets, so
that, as in the Nike Hercules acquisition radar, returns from a
non-fluctuating target in the clear will be cancelled in the can-
cellation circuitry and will not be displayed. Like velocity-
compensated coherent MTI, it cannot eliminate chaff to the extent
that its internal motion decorrelates the return over intervals
corresponding to a pulse repetition period. This situation can
occur when a search radar illuminates chaff that is either in
highly turbulent air or is distributed through a range of altitudes
where vertical wind shear produces a large spread of dipole radial
velocities.

There appear to be several schemes for achieving non-
coherent MTI operation. One of these, used in the FPS-20 anti-
chaff receiver, delays the amplitude-limited IF signal by one pulse
length and then compares this signal with the undelayed signal in
a phase detector, followed by conventional cancellation. A simpli-
fied block diagram of this type of system is given in Fig. 9.
Another, using quadratic detection of the linearly amplified signal
from a combination of target and chaff, depends on the interpulse
decorrelation in the combined signal, introduced by relative motion
between the two, to change the target signal amplitude on successive

T = PULSE DURATION

$$T = \frac{1}{Prf}$$

MTI VIDEO

RA-2351-232
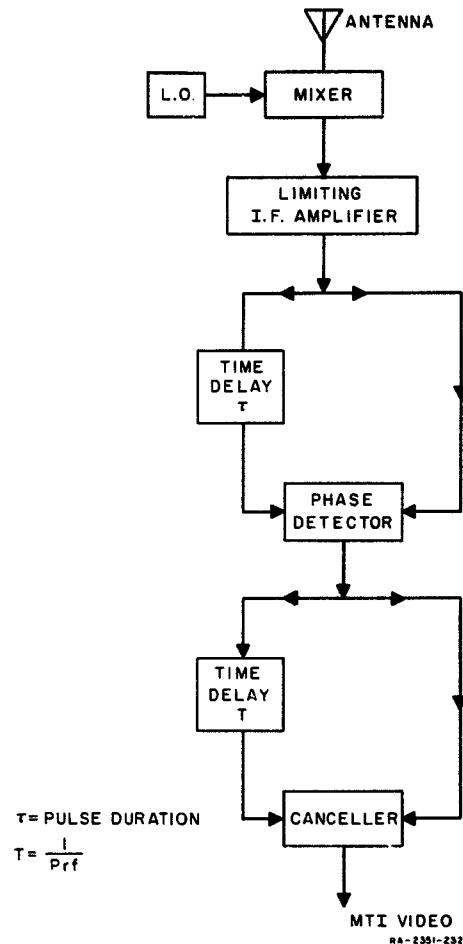
FIG. 9

SIMPLIFIED BLOCK DIAGRAM OF ONE TYPE
OF NONCOHERENT MTI CIRCUITRY

pulses, providing an output from the canceler. Logarithmic ampli-
fication, which, as discussed, compresses the amplitude fluctuations
of uniformly dense chaff at different ranges to some constant level,
also preserves beats between the chaff and target returns. These
beats can be separated from the chaff returns by cancellation cir-
cuitry if the chaff returns are sufficiently well correlated. Range-
gated filtering could be used alternatively to recover the signal-
times-clutter components.

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In recently designed search radars, coherent and non-coherent MTI video may both be displayed on the same PPI scope, either by operator adjustment of noncoherent MTI range and azimuth sectors or by automatic switching provided by a simultaneously scanned storage tube that has recorded video from a previous scan period. The Nike Ajax and Nike Hercules acquisition radar is equipped only with noncoherent MTI, however. For this radar, when using MTI, the visibility of any target, moving or stationary-- unless it is in a chaff cloud or ground-clutter region--depends on pulse-to-pulse fluctuations in the amplitude of the return.

Noncoherent MTI has been proposed for use with tracking radars as well as with search radars to facilitate tracking of targets through corridors and bursts, as well as acquiring of targets in chaff corridors. To accomplish this, the signal return from cross-product terms of chaff and aircraft must be used (instead of being eliminated by the pass band of the tracking cir-. cuit). This signal could be used either to detect the presence of burst chaff, thereupon switching the range servo into automatic coast, or to supply an error signal (to be switched in auto-matically) for tracking through continuously cluttered areas.

b. CW Radar

Pulse radar MTI systems do not, in general, make use of the doppler frequency shift of returns from moving targets as a basis for velocity discrimination, since the change of phase over one short pulse length is very small and extremely difficult to measure. The CW radar can detect these doppler frequencies quite easily with its extended measurement time. Also, by using frequency modulation and waveform analysis, it can achieve range resolution of multiple targets comparable to that of a pulse radar of the same IF bandwidth. Doppler frequency velocity discrimination is free of the problems of blind speed, and can achieve very good suppression of low-velocity targets such as chaff without affecting its response to high-speed targets.* Because of this

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* CW radar does have the disadvantage that distant targets may have to compete with nearby clutter for recognition. If the clutter source is at the same range as the target, however, this will not be important.

and corresponding advantages in discriminating against ground clutter, CW radars for both acquisition and tracking have been incorporated into the low-altitude Hawk missile system.

c. Absolute Velocity Discrimination

(1) _Area MTI_. In contrast to the systems described above, which discriminate on the basis of radial velocity, area MTI is used for "absolute velocity" discrimination. Storing video signals from one radar scan to the next, either on magnetic tape or in a storage tube, it makes a scan-by-scan comparison to detect moving targets, displaying the difference between the present scan and a preceding stored scan. Provision is made for control of the time difference between the scans to be compared, _i.e._, for the storage time or aging of a scan before using it for comparison. Area MTI, of course, has no blind-speed limitations, but is restricted in application by state-of-the-art limitations in dynamic range and resolution of present storage systems. With increased resolution it could be used to eliminate random chaff drops, but regardless of dynamic range it would have no subclutter visibility against targets screened by a chaff corridor.

(2) _Velocity Memory_. To combat the effects of burst chaff, some tracking radars today adjust the range servo response to limit changes in normal radar tracking to those expected in normal aircraft maneuvering. A tracking radar of normal servo bandwidth, for example, may be switched to narrow band or "coast" by the appearance of forward-sown chaff in a gate ahead of the tracking gate containing the aircraft. This class of techniques is referred to as velocity memory. Its effectiveness against forward-sown chaff could be increased by using it in combination with noncoherent MTI.

5. VIDEO CENSORING

All of the anti-chaff techniques discussed above that provide no subclutter visibility for search radars may be considered to be automatic video-censoring techniques whose chief advantage is that they

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prevent the display of clutter which might confuse an operator or over-
load a track-while-scan computer. A method of allowing an operator to
accomplish the same function is employed in the SAGE system and is called
mapping. The operator maps out the clutter area on a PPI display with a
semi-opaque paint, reducing the output of a photocell and preventing
read-out of the clutter signal to the computer input drum. Of course,
any targets in these areas are also rejected.

B. TARGET VISIBILITY AND MTI

In Sec. IV-A a number of techniques have been discussed that may be
used to help protect a radar from saturation in a chaff countermeasures
environment. As important as chaff-suppression techniques may be, how-
ever, target visibility remains the chief objective of radar design. In
view of the modest chaff density requirements discussed in Sec. II, high
clutter levels can be expected to interfere with detection of the target.
It appears, then, that high priority might well be given to techniques
that provide subchaff visibility, i.e., which actually suppress the chaff
returns relative to the target returns. It may be seen from the pre-
ceding section that only one class of techniques promises to provide
significant subchaff visibility for pulsed radars: moving-target indi-
cation circuitry.

The amount of subchaff visibility to be expected from U.S. air
defense radars equipped with MTI circuitry and operational implications
will be discussed in Sec. V. Before examining these, however, it may be
instructive to consider some of the inherent liabilities of MTI inde-
pendent of chaff or clutter return.

One of these, already referred to, is the blind-speed problem. This
is illustrated in Fig. 10, which shows the MTI response curve for the
FPS-20 radar as a function of target radial velocity. This is translated
into an illustrative operational situation in Fig. 11, which shows the
radar response envelope as a function of time for an aircraft flying
140 n.mi. at 600 knots past the radar as indicated, a trajectory that
might commonly be found in an area surveillance system. The lower hori-
zontal scale in each of the plots shows the radial velocity of the target
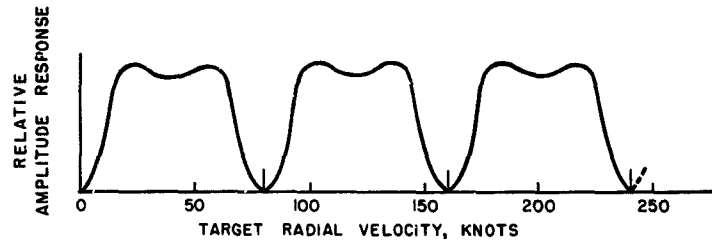
38

FIG. 10

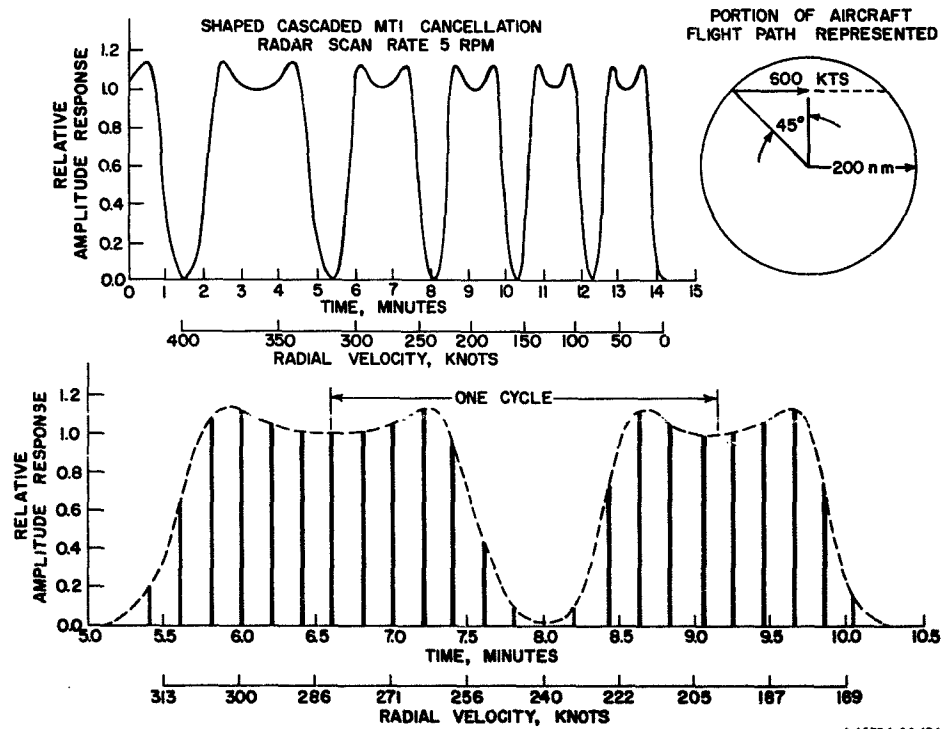FPS-20 THREE-PULSE CANCELLATION MTI RESPONSE
WITH FEEDBACK AT SCAN RATE OF 5 RPM

FIG. 11

ENVELOPE OF FPS-20 MTI RESPONSE TO 600-KNOT AIRCRAFT IN FLIGHT PATH SHOWN

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aircraft corresponding to the time from entry into the 200-n.-mi. circle. The lower plot is an expanded illustration of about two of the cycles centered at about 8 minutes, showing the amplitude of the scan as the height of a vertical black line at the time the scan would occur. For example, around 8 minutes about three scans will be entirely lost due to masking by receiver noise. Following this, one scan will be about three-fourths the usual non-MTI amplitude, followed by six full-amplitude returns, and then decreasing returns again. If the target were barely detectable at the peak of the response curve (because, for example, it is a small target at long range or because a little jamming is added to the receiver noise), then four or five consecutive scans would be lost in the period around 8 minutes and at other times when the radial velocity of the target is in a blind-speed band. With the target aircraft not detectable for between half a minute and a minute, it may be difficult to maintain track on it.

The effects of jamming on an MTI-equipped radar do not appear to be well defined, but there are indications that they may be particularly severe. MTI receivers usually have larger IF bandwidth for a given pulse length than do non-MTI receivers,[10] tending to increase noise jamming vulnerability somewhat. A number of observations of radars equipped with MTI under jamming conditions reveal that the MTI region may be completely saturated when the target is barely screened in the non-MTI region. Field tests have also shown that the Nike acquisition radar repetition rate may become very unstable under jamming, since jamming signals entering the MTI channel may trigger pulses at random intervals. More tests are needed of jamming susceptibility of radars when using MTI.

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V SUBCHAFF VISIBILITY OF U.S. AIR DEFENSE RADARS

In Sec. II-B the question of subchaff visibility arose in considering
the chaff densities required to screen an aircraft from defense radars.
From the radar point of view, of course, the question is how much subchaff
visibility is required to permit target detection and tracking. It is
apparent that a kind of seesaw juggling of parameters is possible here
without any resolution of these questions, as long as both designs remain
flexible. When the radars are designed, however, it is possible to pre-
dict their subchaff visibility to some extent by analysis. When they have
been built, it should be possible to confirm or correct such predictions
in field tests.

In this section two radars are discussed to illustrate the capa-
bilities of two kinds of radars: one that is not designed basically
against chaff, the FPS-20, and one that is, the FPS-28.

A. FPS-20

It may appear to be a harsh judgement against FPS-20 that it is not
designed against chaff--in addition to provision for coherent MTI, it has
a noncoherent MTI receiver that is also called an anti-chaff receiver*--
but its combination of frequency (L-band) and repetition rate (360_{pps})
make even moderate security against windblown chaff difficult with MTI
without encountering prohibitive blind-speed problems.

To illustrate the predicament of such a design, consider two situ-
ations that can defeat it: chaff in shearing winds or turbulent air, and
moving chaff in the same region as ground clutter. Both of these will
give an unwanted return that will clutter the radar display. The co-
herent MTI response of the FPS-20 radar in its best clutter-suppression

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* Actually, the original FPS-20 design did not have the anti-chaff
  receiver; it is a "fix."

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mode at a 5-rpm scan rate is shown in Fig. 10. The noncoherent MTI response about the mean chaff radial velocity is the same except that it has even symmetry about this velocity. It may be seen that after chaff has achieved a velocity dispersion of a few tens of knots, a significantly large return may be expected from it.*

One apparently important operational question occurs at this point. If the chaff is sown in some operationally feasible fashion, how much time is required for the chaff to achieve the velocity dispersion required to produce a significant clutter level against such a radar?

The deflection missile mentioned in Sec. III-B suggests itself as a very suitable means of achieving this dispersion quickly. If the 3-n.-mi. missile suggested by Hult is taken as an example, and if such missiles are fired every ten seconds so as to provide a 50-percent overlap, the chaff trails will be somewhat as shown in Fig. 12.
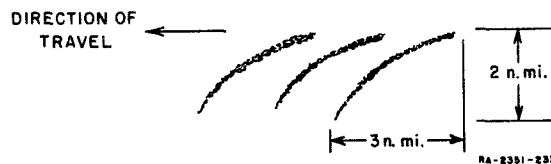

FIG. 12

OVERLAPPING CHAFF TRAILS PRODUCED BY
MISSILES FIRED AT 10-SECOND INTERVALS

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* The frequency power spectrum of amplitude fluctuations in the chaff return before limiting is expected to have a standard deviation equal to $2\sigma_v/\lambda$, where σ_v is the standard deviation about the mean wind velocity and λ the wavelength. The spectrum of the amplitude variations in the output of the phase detector is expected to be nearly the same since the same mechanism that produces the amplitude fluctuations in the return also produces the phase fluctuations. The canceler may be thought of as a high-pass filter for pulse-to-pulse variations. As the velocity dispersion increases, the spectrum widens, and the "filter" passes an increasing fraction of the clutter power spectrum. When the standard deviation of wind velocity about the mean is about 20 knots, the chaff return will be about one-third of what it would be if the chaff were a point target moving at optimum speed (and optimum phase).

In such a distribution pattern, there is at least a 3,000-foot altitude difference in chaff in the same range resolution element of an observing radar. Neglecting further falling, there is a maximum altitude dispersion of about 9,000 feet. According to one source (Ref. 6, p.65), the average wind shear found in the 30,000- to 40,000-foot altitude range is 6 to 12 knots per 1,000 feet of altitude.* In 3,000 feet of altitude one might expect to encounter 15 to 30 knots of velocity difference; over 9,000 feet one might expect 50 knots, at least.

This chaff trail requires only seconds to establish. The bomber penalty is one missile costing a system weight of 60 pounds for each one and one-half miles of penetration distance. For a weight penalty of 4,000 pounds, about one-eighth of the payload of a Bison bomber on a one-way intercontinental mission, a trail of this kind could be extended over 100 miles. The increase in chaff echoing area (no more than a factor of 2 or 3) required by the null in the noncoherent MTI response could almost certainly be made up by using more efficient chaff materials than those assumed by Hult.

A similar situation exists when the mean radial velocity of a chaff cloud in a region of ground clutter exceeds a few knots. The noncoherent MTI cannot cancel the combined return.** This is certainly not a circumstance to be counted on by an enemy, but could prove an important source of interference in radar operation. It is probably fair to say that wherever ground clutter is a problem without MTI, chaff will be a problem with noncoherent MTI for this radar.

It may be readily conceded that the FPS-20 anti-chaff receiver may be helpful in a number of situations. Against chaff sown by a screening missile, for example, it may prevent the radar from being blinded by clutter for several minutes, while the chaff is falling freely and acquiring a velocity dispersion. Enough time might be gained to permit

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* This is the average wind shear about the usual peak wind velocity found at these altitudes.

** This is discussed in some detail in Appendix B.

engagement of the bomber even though it would almost certainly be hidden to the coherent MTI receiver. The question of how critical the time advantage might be has not been investigated.

B. FPS-28

According to information currently available, the experimental model of FPS-28 is to be equipped with three types of MTI designed against chaff:

     (1) Coherent range-gated filter

     (2) Coherent delay-line MTI

     (3) Noncoherent delay-line MTI.

The delay-line MTI can be used with a repetition rate of 1,000 pps.* A government-furnished delay-line canceler is to be used. The characteristics of this canceler are not known.** It may have a response curve similar to that of the FPS-20 radar, with the frequency scale expanded so that the first blind speed is at about 500 knots. The width of the blind-speed band at this speed will depend on the design of the canceler, but will be proportional to twice the width of chaff spectrum rejected. If it is adjusted in the noncoherent mode, for example, to suppress clutter from wind-dispersed chaff that has a standard deviation in radial velocity of 40 knots, a blind-speed band 100 knots wide, or wider, might be expected. If a sufficiently wide blind-speed band were admissible, this mode of operation could, in principle, resist saturation by chaff clutter almost indefinitely. Not enough is known at present to evaluate its possible subchaff visibility as designed.

The problem of a wide blind-speed band around 500 knots is largely eliminated in the range-gated filter MTI by the use of two repetition

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* The radar can also use a repetition rate of 333 pps to extend its unambiguous range, but this does not appear to be attractive for antichaff use.

** The FPS-20 canceler has double (or three-pulse) cancellation with feedback for control of the scanning clutter response. The exact shape of the FPS-28 canceler may not depend on scanning effects, which are not expected to be severe for FPS-28, but rather it may be designed against a wide chaff spectrum.

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rates, 1,200 pps and 800 pps, used on alternate scans.* The high-pass filter used for clutter suppression has a cut-off frequency of 200 cps, corresponding to a radial velocity of about 100 knots. Such a filter can suppress returns from <u>point targets</u> moving at any lower speed. Chaff does not present a point target, however, but one composed of a random assortment of unresolved scatterers; these may give rise to high-frequency fluctuation components in the radar video output that cannot be suppressed by the filter. In order to do this, as discussed previously, the dipoles must achieve a large velocity dispersion.

An idea of the capability of the FPS-28 radar to suppress clutter from windblown chaff while maintaining target visibility can be obtained by formal analysis of the response of an idealized system with the parameters of the FPS-28 range-gated-filter MTI to spectral variations in the chaff return and to an idealized (non-fluctuating) target aircraft return.

Presently available data give the following parameters for the radar:

Operating frequency	510 to 690 Mc
Repetition rates	1,200 and 800 Mc on alternate scans
Rotation rate	6 rpm
Azimuth beam width	1.3°

The range-gated-filter MTI uses a coherent phase reference. The receiver characteristic is linear.

Unfortunately, no measurements are known to have been made of the statistical characteristics of returns from the various types of chaff (foil and fiber dipoles, and "rope") at high altitudes. Measurements of these characteristics would help considerably to provide a measure of performance of modern radars. Until such data are available, it appears

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* This effectively cuts in half the data rate on targets with radial velocities between 300 and 900 knots; <u>i.e.</u>, the result is a 20-second data rate on most aircraft of interest, but the radar is not blind to any target velocity above 100 knots on a pair of consecutive scans.

to be reasonable to assume an extension of the standard Gaussian form referred to in Sec. II for the frequency distribution of power in the chaff clutter. The bell-shaped spectrum curve is centered at the doppler frequency corresponding to the mean radial wind velocity. (This frequency also corresponds to the mean pulse-to-pulse phase shift.)

Calculation of chaff suppression has been made on the basis of a perfectly rectangular filter characteristic. The errors introduced by this assumption are optimistic and will not be significant when the clutter rejection begins to decline, i.e., when the chaff radial velocity has a fairly large mean value or a large standard deviation, or both. These are the conditions of most concern. The idealized gated-filter response function H(f), illustrated in Fig. 13 for one prf, has the periodicity that characterizes a pulsed-radar MTI, the passbands being
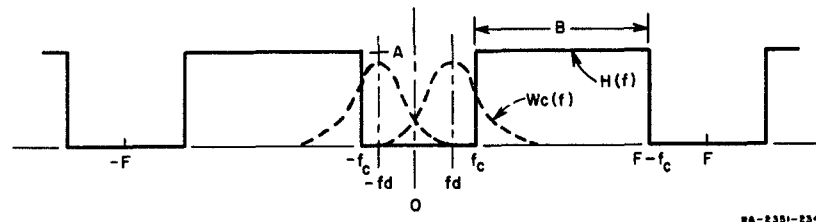
FIG. 13

IDEALIZED GATED-FILTER MTI RESPONSE SHOWN WITH SPECTRUM OF
CHAFF WITH NON-ZERO MEAN RADIAL VELOCITY

symmetrical about odd multiples of half the repetition frequency. The lower cut-off frequency, f_c, for this filter is indicated. F is the pulse repetition frequency, and B the width of the filter passband.

The clutter spectrum, Wc(f), as introduced in Sec. II, is given* by

$$Wc(f) = \frac{1}{\sqrt{2\pi}\sigma} \exp \left[\frac{-(f-f_w)^2}{2\sigma^2} \right]$$

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* It is assumed that the power spectrum of the incoming clutter is not changed by the phase detector.

where σ is the frequency corresponding to rms wind velocity. It is indicated in dotted lines in the figure.

The analysis of the relative chaff attenuation by this system follows the method of R. C. Emerson[2] and yields a figure for "reference gain," $\bar{G}$. This figure is a measure of relative chaff suppression (or relative target enhancement) averaged over all possible target radial velocities. It is discussed in greater detail in Appendix A. The results of the analysis are given in Fig. 14. Both mean and rms wind velocities are plotted. Scanning effects, discussed in Appendix A, are neglected in the figure. The dotted lines indicate the effect of truncating the clutter spectrum at $\pm 2\sigma$ as suggested by Emerson.*
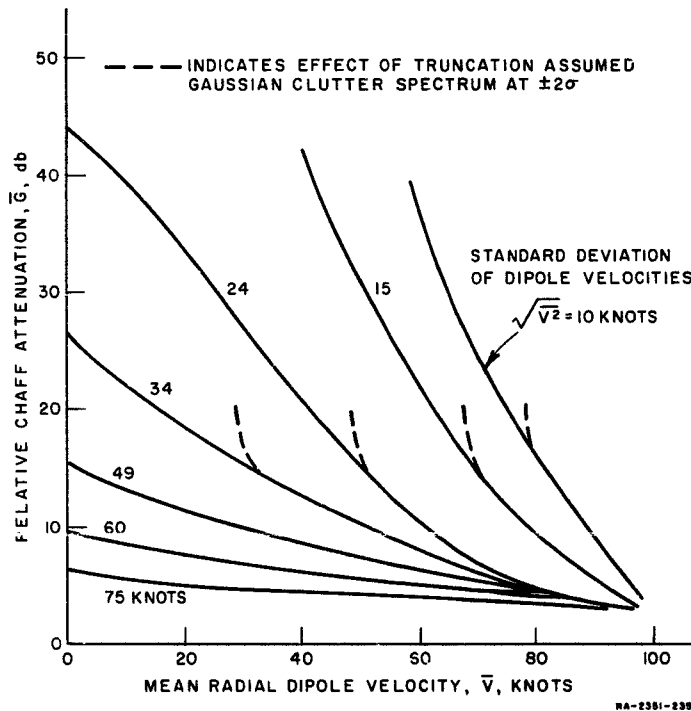

FIG. 14

RELATIVE CHAFF ATTENUATION BY IDEALIZED FPS-28 COHERENT RANGE-GATED FILTER MTI AS A FUNCTION OF WIND CONDITIONS (SCANNING EFFECTS NEGLECTED)

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* The curve is plotted from an expression derived in Appendix A.

The response of the (coherent) range-gated-filter MTI will depend very much on the mean wind velocity, as well as on the velocity dispersion of the chaff, unless velocity compensation is employed.* As illustrated in Fig. 12, at high mean velocities, the attenuation is a less sensitive function of velocity dispersion. The subchaff visibilities at these mean velocities may, however, be critically important in radar operation. The significance of mean wind velocity dependence is that another rather unpredictable variable is introduced,** one that requires additional operational interpretation of the results of the analysis. Two such interpretations will be suggested below. For an idea of mean wind velocities to be anticipated in the U.S., Fig. 15*** may be consulted. This figure, which is self-explanatory, describes conditions in the jet stream belt in the area near the industrial heartland of the U.S.

Chaff sown by a screening missile from an altitude of 40,000 feet might be expected to fall in the manner described in Sec. II. (The effect on the rates of dispersion and fall of the difference between the turbulence created by an aircraft and that created by a screening missile is not known.) From the description a model of vertical dispersion of the dipoles as a function of time can be constructed as follows: From a

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* No mention is made in available sources of velocity compensation for FPS-28; it appears, however, to be highly desirable.

** Wind effects in the MTI clutter suppression produce a characteristic statistical uncertainty; it is difficult to make very general statements because of geographical wind variations, and because of local variations in the mean wind velocity. A mean wind velocity that is uniform over a given area surrounding the radar has a radial component that varies in azimuth from zero to maximum. An uncompensated coherent-MTI radar may thus be blind in one azimuth sector and not in another. The screening value of clutter will depend on the direction of the wind and direction of the attacking bombers. If velocity compensation is used, variations in mean velocity over the chaff-sown region could create problems. The possibility of a combination of wind-chaff relationships unfortunate for the defense is a matter of some concern.

*** Taken from SADR Study, Raytheon Manufacturing Co., date unknown, SECRET, p. 221. This document is a proposal for a Six-Hundred Megacycle Air Defense Radar in which fundamental FPS-28 radar parameters are established.
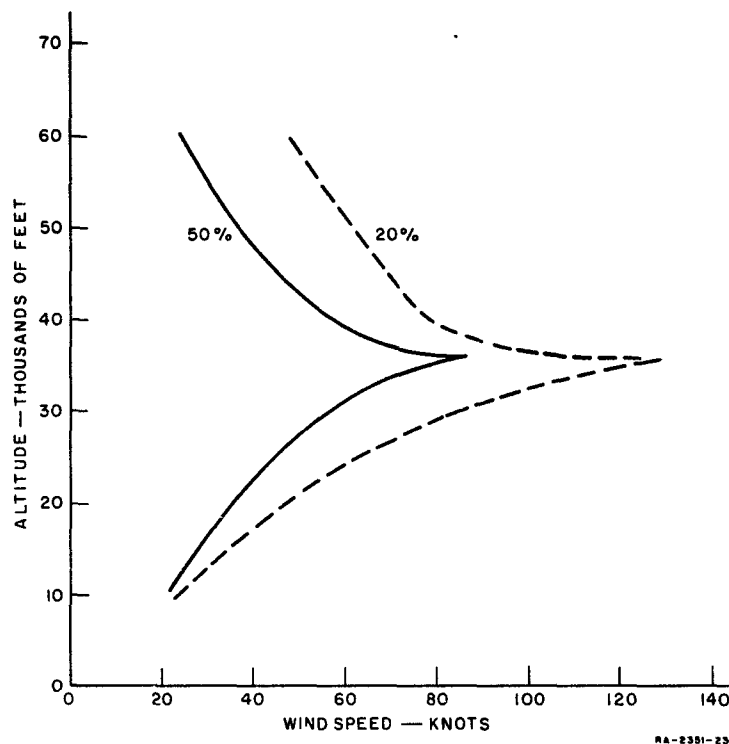
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FIG. 15

SYNTHETIC WIND-SPEED PROFILES—WIND VELOCITIES EXCEEDED
50 PERCENT AND 20 PERCENT OF THE WINTER IN THE WINDIEST
AREA OF NORTH AMERICA (NORTHEASTERN PART)

very small vertical spread immediately after dispensing, the chaff cloud
increases its vertical dimension at the rate of about 600 feet per
minute (the rate of fall of the fastest falling chaff) for about seven
minutes, after which the cloud, about 4,000 feet in height, settles
down uniformly at a rate of 300 feet per minute. The dipoles in the
cloud may be distributed approximately normally in altitude within the
4,000-foot core. According to the wind shear figures quoted previously,
a shearing gradient of about 25 to 50 knots can be expected across this
core. If this gradient is constant in altitude, a standard deviation in
dipole velocities of about 6 to 12 knots would result. The mean velocity,
as may be seen for conditions represented in Fig. 14, might be expected
to be around 60 to 80 knots or greater in the 30,000- to 40,000-foot

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altitude range.[6] Under these conditions, the FPS-28 could be expected
to have 10 db or more of subchaff visibility--sufficient, perhaps, to
reduce the clutter level to receiver noise level while displaying the
target aircraft* (assumed non-fluctuating). At low velocity deviations,
however, the radar response is sensitive to changes in mean wind ve-
locity. It should be pointed out that wind shear gradients as great as
160 knots in 2,000 feet of altitude are known to occur. If such shear
should result in a standard deviation of around 50 knots in dipole radial
velocity, with the high mean velocity that such winds would have, the
radar would have almost no subchaff visibility. This effect would not be
expected to last very long, not more than a few minutes, unless fresh
chaff were sown into the shearing winds.

Because of its design features, the FPS-28 would be expected to fare
better against the deflection-missile chaff trail than the FPS-20 radar.
We may represent the spectrum of the double trail of Fig. 12 somewhat as
shown in Fig. 16, where f_1 corresponds to the mean radial velocity of the
upper trail and f_2 to that of the lower trail. The width of each is pro-
portional to the standard deviation of velocities among the dipoles. If
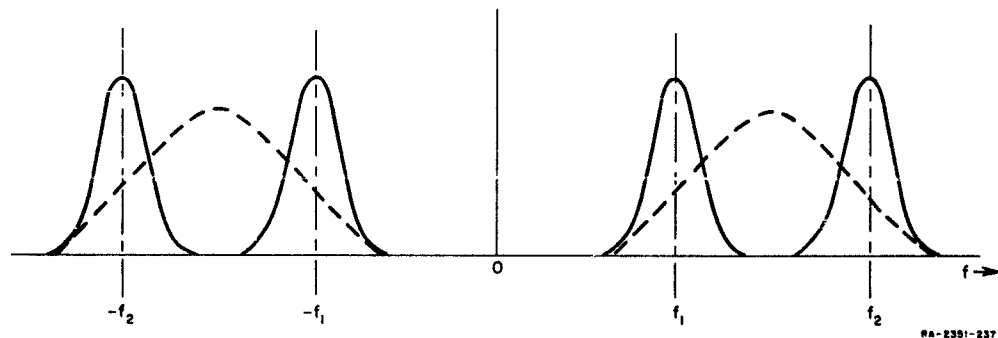the mean velocities are spaced by 30 knots and are both below 100 knots,

FIG. 16

APPROXIMATE SPECTRUM OF DOUBLE CHAFF TRAIL
BEFORE AND AFTER ALTITUDE DISPERSION

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* Most PPI displays have only a 10-db dynamic range so that a signal
  10 db greater than clutter residue will appear at full intensity on
  the display.

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the higher one will produce considerably greater clutter residue (clutter after filtering) than the lower as long as the individual spectra are fairly narrow. As dispersion of dipole velocities takes place, however, the two spectra will tend to merge, as indicated by the dotted lines, with a resultant spectrum that assumes an approximately normal shape. Thus Fig. 14, which assumes a normal or Gaussian spectrum, may again be used directly to estimate subchaff visibility. (A time of the order of several minutes might be required for this dispersion.) Using the same sowing pattern as indicated against FPS-20, and taking as the mean wind radial velocities 40 and 70 knots for the two trails, the radar even without velocity compensation can be expected to have good subchaff visibility initially, unless the chaff is immediately dispersed in velocity by turbulent air. If the chaff falls at the rates already described, however, after a few minutes the spread in dipole velocities will have widened the spectrum appreciably. The standard deviation may be on the order of 20 or 25 knots, or more. If the mean radial velocity were 75 knots, the radar would have only a few db of relative chaff attenuation. It will be observed that in Fig. 15 the lower trail has been assumed to have the larger mean radial velocity. This is characteristic of altitudes above 35,000 feet. If the well-dispersed chaff cloud should encounter a high-mean-velocity wind at lower altitudes, the clutter residue (after filtering) would increase, and the subchaff visibility could approach zero.

It is not known at present whether the problem of sensitivity to mean wind velocities is to be met in this MTI mode by velocity compensation, by overlapping coverage of adjacent radars, or by a combination of both measures. It can be deduced from Fig. 14 that velocity compensation could greatly increase the effectiveness of the MTI (unless ground clutter were severe) in attenuating the chaff, which would then have to acquire a very high velocity dispersion in order to clutter the display sufficiently to hide the target. (For example, with the effective mean wind velocity reduced to zero by velocity compensation, a deviation of 50 knots would only reduce $\bar{G}$ to about 15 db.) Of course, under some circumstances, the chaff might eventually achieve the required dispersion.

The effects on target visibility of the blind-speed band from 0 to 100 knots may be of interest. The unambiguous radar range is about 100 n.mi. for a repetition rate of 800 pps.* If an airplane traveling at 1,000 fps flies the tangential course indicated in Fig. 17, so that its nearest approach to the radar is 70 n.mi., it will not be visible to the radar for some 24 n.mi. of its travel, occupying a time of about 140 seconds or about 14 scans of the radar. This suggests that not all blind-speed problems can be solved by using multiple repetition rates. The operational seriousness of this problem has not been considered.
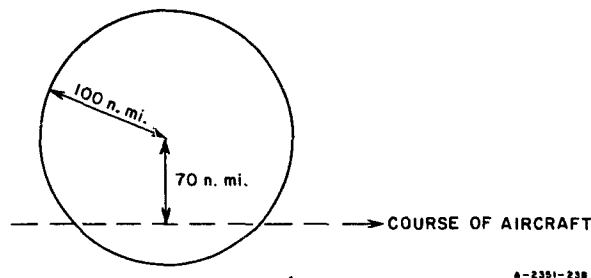

FIG. 17

TANGENTIAL COURSE OF AIRCRAFT PAST RADAR
FOR ILLUSTRATION OF BLIND ZONE

The general conclusion that emerges from these considerations is that what is purchased by the inclusion of uncompensated coherent range-gated MTI in the radar is a statistical probability (unevaluated as yet) of a delay of some time before the chaff screen becomes effective. It appears that this time delay could be increased significantly under most conditions by the inclusion of velocity compensation.

The figures used in the foregoing discussion are thought to be conservative, as are the assumptions of a nonfluctuating target and a

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* It is not known that the FPS-28 is planned to display its full range capability on the scans when it uses an 800-pps repetition rate. This might, however, be desirable in view of the radar's limited range in this mode. The example, in any case, is illustrative.

rectangular cut-off filter. Possibly more extensive and thorough
examination of a greater variety of anticipated attacks might be
warranted. It is felt that the greatest deficiency in the examination
of this radar's chaff suppression capability is omission of a detailed
investigation of the noncoherent delay-line MTI. No evaluation of the
radar would be complete without examining the capabilities of this mode.
A decisive analysis would have to use better data on the statistical
parameters of return from windblown, high-altitude chaff than are
presently available.

VI THE STATUS OF CHAFF THREAT EVALUATION

The foregoing investigation of chaff as a possible threat to
U.S. air defense radars has led, perhaps inevitably, to more questions
than answers. These questions will be summarized briefly in this
section.

A. WIND EFFECTS

Already mentioned is the lack of information on the statistical
characteristics of chaff sown at high altitudes under various wind
conditions and the variations in these characteristics. In the liter-
ature a reference has been noted to "wind shear measuring circuitry"
to be employed on U.S. radars, but no details of this circuitry were
given, and no reference to its use has ever been found. Presumably
this could be a form of "correlation detector" giving outputs pro-
portional to the difference between consecutive pulses, every other
pulse, every third pulse, etc., but how such a device could aid in
achieving subchaff visibility is not at all clear.

Other kinds of aerodynamic effects present uncertainties. For
example: Are there any mechanical design considerations that limit
the efficiency of chaff dipoles when they must withstand the impacts
of launching from a supersonic screening missile without crumpling or
birdsnesting? Or can high efficiency of chaff materials be realized
in such operations?

It is considered desirable, in order to refine somewhat the gross
predictions of this report, to extend the analytical work to include
nonlinear receiver effects. This work may have already been accomplished
elsewhere, but is unknown to the author.

B. SIGNIFICANCE OF TIME DELAYS ON DEFENSIVE OPERATIONS

The time delays between sowing and full effectiveness of chaff
against MTI radars may turn out to be operationally important. Perhaps

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their effects cannot be profitably investigated further, however, until better experimental data are available.

A time-delay question similar in basic nature to that for MTI but opposite in effect is encountered with CRAFT techniques, where a delay on the order of minutes is required for sufficient chaff dispersion to permit decorrelation of returns by means of pulse-to-pulse frequency change.

Another time delay of interest is the reacquisition time of the tracking radars of various systems after they have been pulled off target by, say, deflection-sown chaff. Long delays could decrease chaff requirements against these radars on the part of the bombers.

Effects of chaff on specific U.S. SAM system radars have not been mentioned specifically in this report, nor have effects on constellations of such systems. Some thinking along these lines has been done in this country. Hult (Ref. 5, p. 3), for example, has pointed out that if the number of trails sown by a group of aircraft exceeds the number of tracking radars that can be used to search them, chaff may be useful if sown only against search radars; otherwise, it would have to be sown against the trackers as well.

C. ECCM COMPATIBILITY

Perhaps, in view of the tendency to think in terms of anti-chaff fixes, the basic differences in jamming and chaff MTI radar CCM should be emphasized. The radar frequency must be high, for example, to force wide-band barrage jamming, but must be low to permit effective chaff suppression by MTI. The radar IF bandwidth should be narrow against jamming, but must be wide to permit high-resolution discrimination against chaff. Pulse-to-pulse frequency jumping against jamming cannot be used with MTI. Basic incompatibilities of this kind have led to the investigation of the compromise offered by the CRAFT technique and to some consideration of such complex equipments as bistatic noise radars at high frequencies.

D. WARHEAD SIZE

No discussion has been given in the preceding sections of the effects of defensive missile warhead size on the effectiveness of a chaff trail or corridor against a defense system. It may certainly be possible to pattern-blast the cloud even though no aircraft are visible within it. If high-explosive warheads are used, such a method would not be expected to offer a high-kill probability. Nuclear warheads, however, if available, might be quite effective if used in this fashion. It may even be possible and useful to melt holes in the clouds by large-yield thermonuclear weapons, but this is sheer speculation.

E. ECCM OBJECTIVES AND MEASURES OF EFFECTIVENESS

One of the fundamental questions arising from an investigation of this kind is that of ECCM objectives. It appears that, depending on one's ECM philosophy, a number of measures of effectiveness may be thought to be important. For example: If the primary objective of radar ECCM is held to be prevention of data saturation, then subchaff visibility may, perhaps, be sacrificed quite freely. There is a similar question at the strategic level: Is the strategic function of radar protection primarily economic or military? That is, are we trying, for example, to force the Soviets to more costly equipment and methods (that will still have a tactical advantage over our radars), or are we thinking primarily in terms of radar protection against present-day Soviet capabilities? This question appears to reflect the choice emphasized in this report between anti-chaff fixes and anti-chaff design. It appears, in general, that whereas anti-chaff design as embodied in the FPS-28 radar could make the tactical usefulness of chaff very questionable, fixes to present U.S. radars will not provide a degree of security against present Soviet chaff capabilities that could be considered a basic deterrent to their use against U.S. defenses.

APPENDIX A

CALCULATION OF REFERENCE GAIN OF RANGE-GATED FILTER MTI

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CALCULATION OF REFERENCE GAIN OF RANGE-GATED FILTER MTI

The significance of the reference gain of the system may be seen from the derivation below, taken from Emerson (Ref. 11, p.11). The uncancelled power residue at the output terminals of the filter unit depends on the input signal and clutter power levels, and on their respective power spectra. If a moving-target signal is present, this residue will be denoted R (C, S, v) where $\underline{C}$ is the clutter power present at the input terminals of the filter, $\underline{S}$ is the input power for the target signal, and $\underline{v}$ is the target velocity. In the absence of a moving-target signal, the residue will be denoted R (C, 0, --). The incremental increase in output power residue that can be credited to the presence of a moving target is

$$R \ (C, \ S, \ v) - R \ (C, \ 0 \ --) \ ,$$

and it will be called the output <u>signal</u> power. Since the output <u>clutter</u> power is R (C, 0, --), the output-signal to clutter-power ratio, designated X_0, is given by the ratio

$$X_0 \ = \ \frac{R \ (C, \ S, \ v) - R \ (C, \ 0, \ --)}{R \ (C, \ 0, \ --)} \ .$$

The input-signal to clutter-power ratio, designated X_i, is simply S/C. In terms of these quantities, the gain, $G(v)$, is defined by

$$G(v) \ = \frac{X_0}{X_i} \ = \ \frac{C}{S} \cdot \frac{R \ (C, \ S, \ v) - R \ (C, \ 0, \ --)}{R \ (C, \ 0, \ --)} \ .$$

This quantity can in general be expressed in factored form as a product, <u>i.e.</u>,

$$G(v) \ = \ \bar{G} \cdot E(v)$$

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where $\bar{G}$ is independent of target velocity and $E(v)$ is independent of clutter characteristics. $\bar{G}$ is numerically equal to the average of $G(v)$ over all target velocities, $\underline{v}$, and so can be construed as the "expected" gain in the probabilistic sense that a target whose velocity is unknown is equally likely to be moving at all velocities. It is desirable, of course, for $\bar{G}$ to be as large as possible. The form of the output power residue, in general, is the sum of a number of terms arising from a number, say $\underline{N}$, of pulses:

$$P \sum_{j=0}^{N-1} \sum_{k=0}^{N-1} a_j a_k \, \rho(t_j - t_k)$$

where $\underline{P}$ is input power, the summation with weighting functions a_j and a_k representing the MTI circuit's combining of successive pulses; and $\rho(t_j - t_k)$ accounts for the decorrelation of the return over an interval of length $t_j - t_k$, the time between the jth and the kth pulses. It is assumed in this analysis that target returns are perfectly correlated, so that $\rho_s(t_j - t_k) = 1$.

Emerson derives an expression for $G(v)$ for the type of system here examined by considering the input to the filter to be an infinite train of pulses. The expression given above takes the form

$$G(v) = \frac{C}{S} \cdot \frac{\left[S \displaystyle\sum_{j=0}^{\infty} \sum_{k=0}^{\infty} f(t_j)f(t_k)\rho_s(t_j - t_k) \; + C \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} f(t_j)f(t_k)\rho_c(t_j - t_k) \; - C \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} f(t_j)f(t_k)\rho_c(t_j - t_k) \right]}{C \displaystyle\sum_{j=0}^{\infty} \sum_{k=0}^{\infty} f(t_j)f(t_k)\rho_c(t_j - t_k)}$$

where $f(t)$ is the impulse time response function of the filter, and t_j represents the times of arrival of the pulses in the gated channel; the normalized autocorrelation of the return from the target is $\rho_s (t_j - t_k)$.

Since

$$\rho_s (x) = \int_{-\infty}^{\infty} e^{i\omega x} W_s(f)df$$

and

$$\rho_c (x) = \int_{-\infty}^{\infty} e^{i\omega x} W_c(f)df \, ,$$

$$G(v) = \frac{\int_{-\infty}^{\infty} H(f)W_s(f)df}{\int_{-\infty}^{\infty} H(f)W_c(f)df}$$

where $H(f) = \left| \sum_{j=0}^{\infty} e^{i\omega t_j} f(t_j) \right|^2$ is the gated-filter response function in Fig. 13.

If the target echoes are perfectly stable, then $W_s(f) = 1/2[\delta(f+f_d)+\delta(f-f_d)]$ where $\delta(x - y)$ is the unit impulse function at $x = y$, and f_d is the doppler frequency ($= 2v_r/\lambda$) due to target radial motion. Since $H(f)$ is symmetrical about $f = 0$, the system gain reduces to

$$G(v) = \frac{H(f_d)}{\int_{-\infty}^{\infty} H(f)W_c(f)df} \, .$$

The reference gain, $\bar{G}$, is given by the average of $G(v)$ over $\underline{v}$. Letting $\bar{H}$ denote the average of $H(f_d)$ over f_d, then

$$\bar{G} = \frac{\bar{H}}{\displaystyle\int_{-\infty}^{\infty} H(f)W_c(f)df}$$

and the velocity enhancement factor is just $E(v) = [H(f_d)/\bar{H}]$.

The calculation of $\bar{G}(v)$ for the FPS-28 radar will assume a single repetition rate, 1,000 pps. (The repetition rate so assumed has a negligible effect on the figures calculated.) If, as shown in Fig. 13, $H(f)$ has amplitude $\underline{A}$ in its passband, $\bar{H} = AB/F$.

For the FPS-28 radar, it may be assumed that the range of target radial velocities of greatest interest is 0-900 knots. Accepting the lower data rate over most of this band, and including the blind-speed band from 0 to 100 knots, we might obtain a modified or weighted average for $\bar{H}$, replacing B/F by the ratio of passband of interest to whole band of interest.

It is assumed that the only significant contributions to the clutter residue come from the passbands of $H(f)$ in the intervals 200 to 800 cps and the corresponding negative frequencies, -200 to -800 cps. Then

$$\bar{G} = \frac{AB/F}{\dfrac{A}{\sqrt{2\pi}\sigma}\displaystyle\int_{-[(F+B)/2]}^{-[(F-B)/2]} e^{[-(f-fd)^2/2\sigma^2]}df + \dfrac{A}{\sqrt{2\pi}\sigma}\displaystyle\int_{(F-B)/2}^{(F+B)/2} e^{[-(f-fd)^2/2\sigma^2]}df} \; .$$

Letting $g = (f-f_d)/\sigma$,

$$\bar{G} = \left[\dfrac{1}{\sqrt{2\pi}}\displaystyle\int_{-\infty}^{(F+B-2f_d)/2\sigma} e^{-[(g^2)/2]}dg - \dfrac{1}{\sqrt{2\pi}}\displaystyle\int_{-\infty}^{(F-B-2f_d)/2\sigma} e^{-[(g^2)/2]}dg \right.$$

$$\left. + \dfrac{1}{\sqrt{2\pi}}\displaystyle\int_{-\infty}^{-[(F-B+2f_d)/2\sigma]} e^{-[(g^2)/2]}dg - \dfrac{1}{\sqrt{2\pi}}\displaystyle\int_{-\infty}^{-[(F+B+2f_d)/2\sigma]} e^{-[(g^2)/2]}dg \right]$$

or

$$\bar{G} = \frac{B/F}{\phi[(F+B-2f_d)/2\sigma] - \phi[(F-B-2f_d)/2\sigma] + \phi[-(F-B+2f_d)/2\sigma] - \phi[-(F+B+2f_d)/2\sigma]}$$

where

$$\phi(x) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x} e^{-[(t^2)/2]}dt \ .$$

For the FPS-28 characteristics given, B = 600 cps, and τ = 0.001 second. Replacing B/F as suggested earlier by the ratio 900 knots/ 1000 knots, we get

$$\bar{G} = \frac{0.9}{\phi[(800-f_d)/\sigma)] - \phi[(200-f_d)/\sigma] - \phi[(200+f_d)/\sigma] + \phi[(800+f_d)/\sigma]} \ .$$

This function is plotted for various values of f_d and σ, or rather for the mean wind velocity $\bar{V} = [(\lambda f_d)/2]$ and rms wind velocity $\sqrt{\bar{V^2}} = \lambda\sigma/2$, in Fig. 14.

It has been suggested by Emerson that the Gaussian shape for the clutter spectrum would be more realistic if it were truncated at $\pm 2\sigma$, thereby removing the effects of implied very high fluctuation frequencies which might not be found in the physical situation* or would be below the level of receiver noise. The effects of this truncation of the spectrum are also indicated in Fig. 14.

Azimuth scanning effects have been neglected in the preceding discussion. A comparison may readily be made, however, between the frequencies arising in the output because of scanning and those arising from winds.

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* An argument might be advanced that frequencies up to and including the prf might be expected in clutter fluctuation; no higher frequencies, of course, could be measured.

For an assumed Gaussian-shaped antenna pattern, the rms pulse-to-pulse phase fluctuation incurred in scanning past a distributed target such as a chaff trail is given in Vol. I of the MIT Radiation Laboratory Series (Ref. 9, p. 646) as $1.66/n \sqrt{2}$ radians, where $\underline{n}$ is the number of pulses per beamwidth. At a rotation rate of 6 rpm, beamwidth of 1.3 degrees in azimuth, and repetition rate of 1,000 pps, $\underline{n}$ will be given by 1,000 pulses/sec x 10 sec/360° x 1.3° = 36 pulses/beamwidth. Then rms pulse-to-pulse phase shift is

$$\frac{1.66 \times 57.3°/\text{rad}}{36 \sqrt{2}} = 1.9° .$$

A phase shift of 1.9 degrees at 600 Mc ($\lambda = 0.5$ meter) corresponds to a distance of 1.9/360 x 0.5 = 0.0024 meter = 0.0000014 n.mi. Hence, 1.9°/0.001 sec. corresponds to 0.0014 n.mi./sec. = 5.1 knots.

Scanning then introduces a spread in the spectrum of the chaff return which is equivalent to that produced by internal motion of the chaff of rms velocity $\sqrt{\overline{V^2}}$, about 5 knots. Thus, it does not appear to represent a serious limit to the radar's MTI capability.

APPENDIX B

NONCOHERENT MTI AND CLUTTER VARIATIONS

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NONCOHERENT MTI AND CLUTTER VARIATIONS

In the simple situation of an assumed uniform clutter source and
an assumed moving point target, it is convenient to regard the clutter
signal as providing a reference signal comparable to the coherent phase
reference signal in a coherent MTI. When, however, the situation is
more complicated, e.g., because of clutter variations in range or
fluctuations in time, or because the clutter source has a number of
different radial velocity components, this simple analogy does not
appear applicable, and we must resort to a more fundamental analysis.

The clutter signal from any resolution cell of the radar can be
conveniently represented vectorially, the length of the vector repre-
senting its amplitude, and the angle with a given axis representing its
RF phase as measured, for example, at the radar receiver. Composed of
many individual reflections from bodies within the resolution cell, the
resultant vector represents the net signal that the radar "sees." It
is shown below for one resolution cell containing five individual
reflections. (A cloud of high-frequency chaff dipoles would, of course,
be expected to contain more than five dipoles per resolution cell.)

RESULTANT R

ϕ

REFERENCE PHASE
$\phi = 0°$

A-2381-239

65
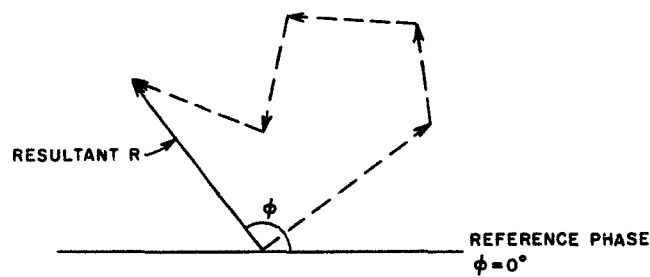
A moving target in this resolution cell returning a signal of amplitude $\underline{S}$ could be represented, if the clutter signal were entirely stable, by a rotating vector from R, as shown below: (Ref. 9, p. 651)

A-2351-240
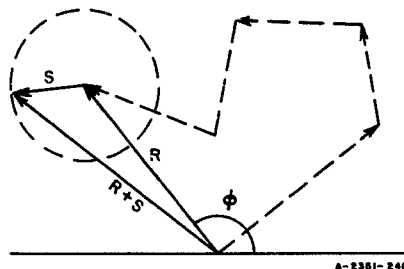
The new resultant is R+S at phase angle ϕ'. As long as the resultant clutter signal, $\underline{R}$, does not change in amplitude and phase, its contribution can be canceled from pulse to pulse, with the variation in the amplitude of R+S giving a signal output from the canceler.

Suppose, now, that the clutter is composed of two independent signals, R_1 and R_2, having a relative radial velocity resulting in a uniform pulse-to-pulse phase shift between them. Let us assume for convenience that each of these signals is of constant amplitude, and that there is no aircraft-type moving target present. We can assume that one of the clutter signals has unvarying phase, or simply use it as a reference phase.* Then, depending on the relative signal amplitudes, R_1 and R_2, as shown, the resultant amplitude may exhibit large periodic fluctuations.

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* The phase of this signal on its arrival at the receiver may be assigned a value zero for each pulse, and the phase of simultaneously arriving signals referred to or measured from it. (In noncoherent MTI no phase reference signal is generated within the receiver.)

A-2391-243
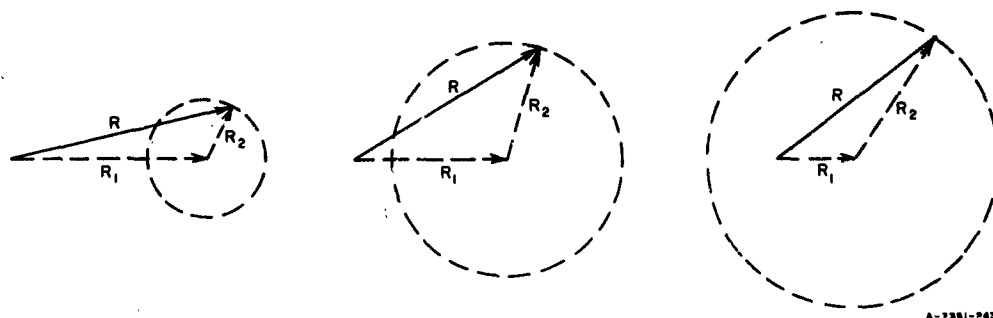
In a high-frequency, low-repetition-rate radar, even a low relative velocity between R_1 and R_2 can produce large pulse-to-pulse angular rotations in R_2 relative to R_1. At the L-band frequency of FPS-20, for example, and at its pulse repetition rate, a 20-knot relative velocity will produce about a 90-degree rotation between pulses.

The FPS-20 radar, however, uses a more complicated system than amplitude detection for obtaining its noncoherent video input to the canceler. By delaying part of the return by one pulse length and phase-comparing it with its undelayed counterpart, it obtains an output that is a function of the phase difference between the returns in successive resolution cells. When this detection output is subtracted from that from the preceding pulse return, it gives a canceled output that is a function of the pulse-to-pulse variation in the phase difference between returns from consecutive resolution cells.

The simple vector diagrams above cannot represent this situation well. To represent it, consider the situation illustrated below:


A-2391-244
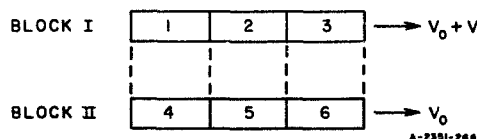
Blocks I and II are separate blocks of clutter at different altitudes with a differential radial velocity $\underline{V}$. Each is three resolution elements long; Groups 1 and 4 are in resolution cell A; 2 and 5 are in B, the next; and 3 and 6 are in C, the last. Cell A will have an

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instantaneous resultant R consisting of the vector sum of the two components from 1 and 4. B and C will be similarly composed. On each pulse the phase differences, ϕ_1 between R_A and R_B, and ϕ_2 between R_B and R_C, will yield the phase detector output.
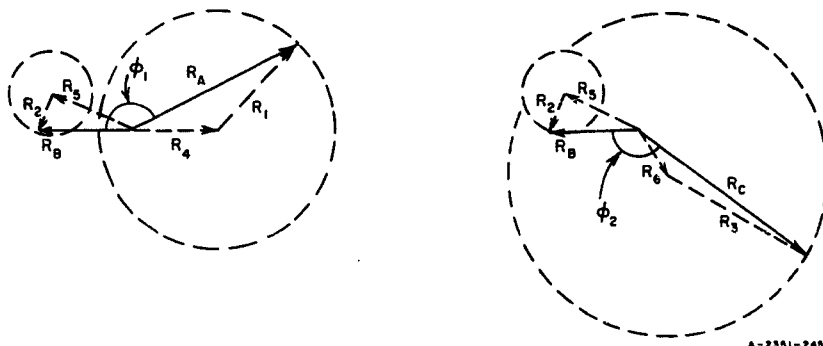
Our immediate concern is the effect on the phase detector output of the relative velocity V between clutter blocks. Neglecting, then, the phase and amplitude variations which may occur within Blocks I and II between pulses, we can consider that R_1, R_2, and R_3 rotate through an angle θ which for a V of 20 knots we shall take to be 90 degrees clockwise. R_4, R_5, and R_6 will retain their phase positions on the diagram.
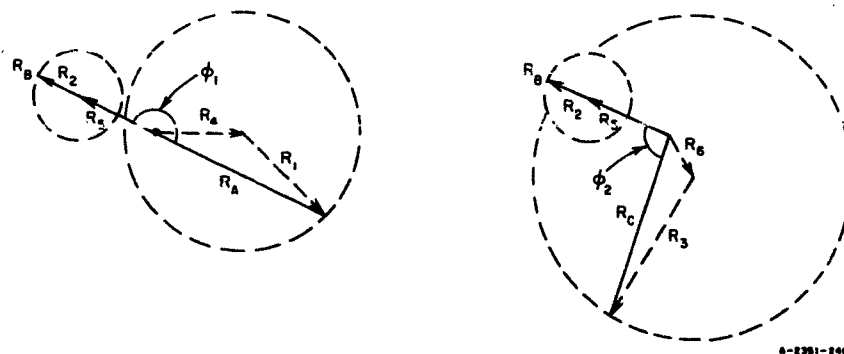
From these rough vector diagrams we can draw some general conclusions. It will be noted that whereas ϕ_1 has undergone a change of about

25 degrees during the repetition period, ϕ_2 has changed by about 45 degrees.* The difference between these numbers can be seen from the vector diagrams to be attributable to greater variation in range (not in time) of the clutter amplitude between B and C than in that between A and B. Such range-to-range fluctuations are a characteristic feature of chaff return, as discussed in Sec. II.

If all the amplitudes of the individual returns above, $(R_1, R_2, R_3,$ etc.) were equal, then the first-order effects described above would produce a cancelable output. The dependence of phase angle on amplitudes of unequal components, however, makes it very likely that for a radar with short wavelength and high repetition rate, uncancelable phase shifts would occur as a result of mean velocity differences alone, producing strong clutter on the display. Dispersion effects in the two blocks would also, of course, contribute to this clutter.

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* The radar response depends, of course, on the ability to cancel the phase detector responses to signals having these phase differences; 25 degrees corresponds to the shift resulting from a mean wind velocity of 5 knots; 45 degrees to a shift resulting from a mean wind velocity of 10 knots. A target characterized by a 45-degree pulse-to-pulse phase shift gets about one-third of maximum response. Considerably larger phase shifts could, of course, readily occur in high-speed winds.

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